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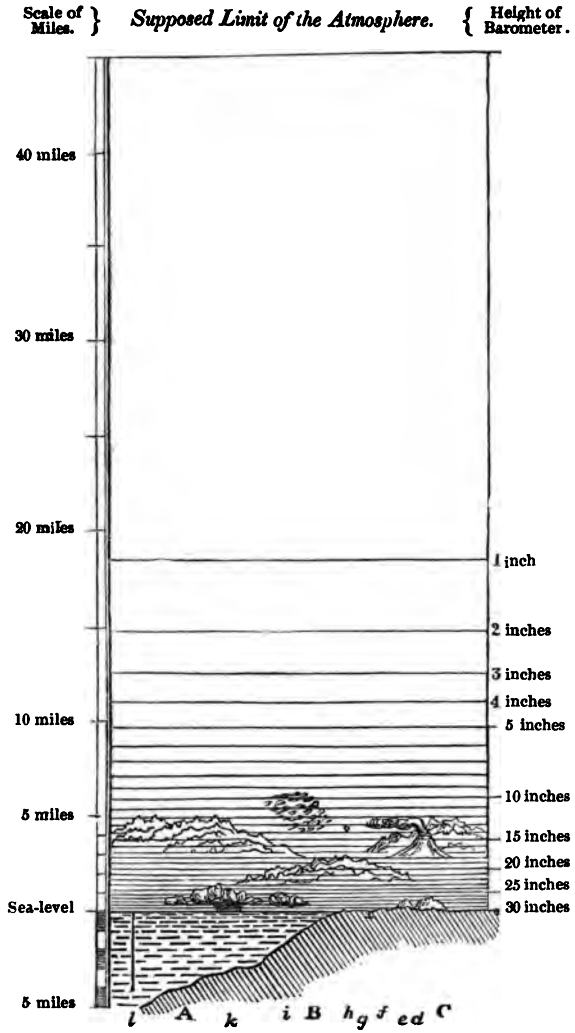

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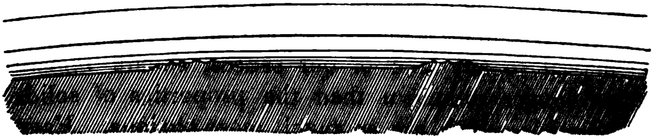
PNEUMATICS.

1. Our knowledge of the atmosphere, as revealed to us by the united aid of Chemistry and Pneumatics, is one of the greatest triumphs of modern science. It was not until the close of the last century that air was removed from the list of ancient elements, and was proved to consist of two gases of essentially different chemical properties. Its physical properties were discovered earlier; but our present extensive knowledge of the atmosphere, considered chemically, physically, and meteorologically, is chiefly the fruit of modern investigation, the result of improved instrumental aid and methods of research. And it is natural to suppose that the working parts of so vast and complicated a machine as the atmosphere, which can be scarcely said to appeal to any one of our senses, should remain much longer unknown than the properties of solids and liquids, which are so much more obvious. Even the heavenly bodies, although appealing to only one of the senses, and removed from us by vast distances, are calculated by their beauty and the regularity of their motions to attract attention, much more than an invisible attendant, which, although constantly present with us, performs most of its varied offices in silence and in secret.

The atmosphere or sphere of gases (ἀτμοὶ) is the general name applied to the whole gaseous portion of this planet; as the term *ocean* is applied to its liquid, and *land* to its solid portions. Being much lighter than either land or water, it necessarily floats or rests upon them; but unlike the ocean, which is confined to the depressions of the solid surface, and covers only about three-fourths of it, the atmosphere is in sufficient quantity to cover the highest mountains, and to rise to nine or ten times their height above the sea-level, so as to form a layer over the whole surface, averaging probably between forty and fifty miles in thickness; which is about as thick in proportion to the globe as the liquid layer adhering to an orange after it has been dipped in water. The accompanying figure (Fig. 1) will convey an idea of the proportion which the highest mountains bear to the curvature of the earth and the thickness of the atmosphere. The concentric lines divide the atmosphere into six layers, containing equal quantities of air, showing the great compression of the lower layers by the weight of those above them.

Fig. 1.
Supposed height of the atmosphere.



3. The atmosphere consists essentially of two gases, called *oxygen* and *nitrogen*. In its pure state oxygen is remarkable for the energy with which it promotes combustion and respiration and other chemical changes. An iron or steel wire, heated to redness at one extremity, and plunged into a vessel full of this gas, will *take fire and burn* most brilliantly. If an animal be

placed in pure oxygen, its pulses will throb with increased rapidity, and it will die from excess of vital action. The properties of nitrogen, on the contrary, appear to be of a negative character. It supports neither combustion nor respiration, and on the latter account it was formerly called *azote**. It does not appear, however, to have any poisonous properties, like some other gases; an animal cannot live in it, simply from the absence of oxygen, not because nitrogen is in itself prejudicial: on the contrary, its uses in the atmosphere appear to be simply those of a dilutent; it subdues and modifies the activity of the oxygen, and in order to do this most effectually it exists in the atmosphere in much greater abundance than the oxygen. Every atom or particle of oxygen is accompanied by four atoms or particles of nitrogen; that is, if any measure or volume of air be separated or decomposed into its component parts, the nitrogen will occupy four times as much space as the oxygen. It is, however, an important property of gases to mingle or become *diffused* together so intimately, that, although oxygen is somewhat heavier than nitrogen, these two gases always exist in the atmosphere in the proportion of 1 to 4, and this without any regard to the localities from which samples of the air may be taken. In the crowded courts of our metropolis, as well as in the breezy downs of the country, in the arid deserts of Arabia, in the open ocean, in the polar regions, at heights accessible only to the balloon, in the fever hospital, and in the flower garden, the proportion of these two essential ingredients of the atmosphere remain constantly the same.

And this fact will appear the more wonderful when we consider the innumerable sources of vitiation tending to destroy the useful properties of the oxygen by depriving it of its powers to support life and combustion. Indeed these two very actions are the chief means of vitiating it, for during the combustion of our lamps, and candles, and fuel, and during the respiration of animals, a quantity of carbon is liberated, every six parts of which (by weight) unite with 16 parts by weight (or about 3600 times their own bulk) of oxygen to form a compound gas called *Carbonic Acid*, which resembles nitrogen in not supporting animal life or combustion; but it differs from nitrogen in being soluble in water, having an acid reaction, and some other characteristic properties which readily distinguish it from that inert element. Carbonic acid is always present in the atmosphere in small but varying quantities; and it is because the quantity is liable to change that this gas is not reckoned as one of the essential constituents of the atmosphere. In 10,000 volumes or measures of atmospheric air the mean proportion of carbonic acid is only five volumes; the proportion, however, is subject to constant variation, from 6·2 as a maximum to 3·7 as a minimum. Near the surface of the earth the proportion of carbonic acid is greater in summer than in winter, and during night than during day. It is also rather more abundant in elevated situations, as on the summits of high mountains, than in the plains; and although this gas is considerably heavier than its own bulk of pure atmospheric air (its specific gravity being about 1·52), yet it appears to be diffused through the whole mass.

---

* From α ζωη, privative of life.

When we consider that the innumerable animals which inhabit both the land and the water all depend more or less upon oxygen for their very existence; that combustion of various kinds, as carried on in our daily operations, that fermentation and other processes all *consume* immense quantities of oxygen, *i. e.* convert it into steam and carbonic acid, chiefly the latter, it does indeed appear wonderful that the quantity of carbonic acid in the atmosphere should be so small. By a beautiful arrangement, however, the carbonic acid thus formed is made to be the food of the vegetable world. The green parts of plants, under the influence of light, absorb carbonic acid, retain and assimilate the carbon, and restore the pure oxygen to the air. During the night, however, plants absorb oxygen and give out carbonic acid; but in the course of the twenty-four hours they give out considerably more oxygen than they consume, and in this way a compensation is made for the loss of oxygen occasioned by respiration and combustion.

The atmosphere also contains a variable quantity of aqueous vapour, arising partly from combustion as above mentioned, but chiefly from contact with the surface of the sea, lakes, rivers, and moist soil. In 100 parts by weight of atmospheric air the mean quantity of watery vapour is nearly one part and a half. The amount, however, varies according to the temperature. At 50° (the mean temperature of England) the air can contain $\frac{1}{120}$th of its weight of water in an invisible state, without forming cloud, mist, or rain. It does not always contain so much, but the quantity cannot exceed this, without a portion being precipitated in a visible form. At a higher temperature, however, more vapour could remain invisible; thus at 82° (the mean temperature of the equator) the air may contain as much as $\frac{1}{43}$rd of its weight of invisible steam; and air that contained only $\frac{1}{120}$th would be injuriously *dry*, though the same air cooled down to 50° would be at its maximum of humidity.

There are other accidental ingredients in the atmosphere which are too numerous and in too small quantity to take account of. As the sea contains a little of everything that is soluble in water, so the atmosphere contains a little of everything capable of existing in the gaseous form at common temperatures. Ammonia, which is a compound of hydrogen and nitrogen, is present in the atmosphere, and is supposed to be the source of nitrogen in plants; while in crowded cities, and in the neighbourhood of gas-works, smelting furnaces, sewers, stagnant pools, sulphur springs, &c. there is much local contamination of the air from the presence of different gases. Various forms of infection, malaria, and marsh-miasma probably arise from the presence of noxious gases in the air.

4. This invisible compound fluid, the atmosphere, possesses many of the properties of solid matter, and also many that are peculiar to fluids. In a former treatise the chief properties by which solids are distinguished from fluids were pointed out; but it is now necessary to consider these and other properties more fully with reference to the atmosphere.

In common with matter in every state, the air possesses *impenetrability*. It is obvious to the senses, as far as regards solids and liquids, that no two bodies can occupy the same place at the same time; in order that one body should occupy the place of another, it is obviously necessary that the second should move away or be displaced; but the evidence of the senses fails us in the case of air. If we step into a bath completely full of water, a portion will overflow precisely equal in bulk to that part of the body which is submerged; the same thing takes place in an *empty* bath as it is called, or a bath full of invisible air, and hence called empty. When a person enters a room, a quantity of air precisely equal to his own bulk is displaced, and escapes by the door, or window, or other opening. But the proof of the impenetrability of air may be made more obvious by the following experiment. Plunge an inverted goblet into a vessel of water, keeping its edge horizontal, and it will be found that, to whatever depth we plunge the goblet, the water will not fill it entirely. The air will be *compressed* into a smaller space, but not annihilated or displaced. At a depth of 34 feet below the surface of the water, the vessel containing the air will be half filled with water; at 100 feet it will be three quarters filled; at 1000 feet it will be filled to within a thirtieth; but even this small remaining space contains *all* the air which previously filled the vessel, and in drawing it up again to the surface the air will expand to its original bulk and drive out all the water. In fact, we can only get rid of the air by *inclining* the vessel, when so much of the air as is below the level of the highest part of its mouth will rise in bubbles through the water and escape; and in this way all the air in the vessel must be *decanted* or *poured up* before it will be filled with water.

5. The *impenetrability* of air is alone sufficient to prove it to be a material body, and, though formerly supposed to be without *weight*, it is now well known to possess this property in common with all other known states of matter; that is, it obeys the attractive influence of the earth and gravitates towards its centre. The proof that air has weight will be abundantly shown hereafter, when we come to speak of the barometer; but for our present purpose the following experiment will suffice:—A copper flask of the capacity of 100 cubic inches, furnished with a stop-cock, is fixed to one extremity of the arm of a balance, and accurately counterpoised by weights in the opposite scale.

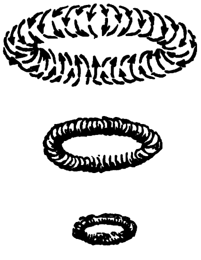
An exhausting syringe (an instrument to be described hereafter, 10) is then screwed upon the neck of the flask with the stop-cock open, and by working the syringe nearly the whole of the air can be pumped out of the flask. On closing the stop-cock, to prevent the admission of the air, and detaching the flask from the syringe, it is again weighed, and is found to have lost about 31 grains; or, in other words, 100 cubic inches of air weigh about 31 grains. On opening the stop-cock, the air will be heard to rush in, and the equilibrium of the balance will be restored as before.

If, instead of screwing the copper flask to an exhausting syringe we screw it to a *condensing* syringe, we can force or condense a quantity of air into the flask, in addition to what it naturally holds. After a few strokes of the condensing syringe the stop-cock of the flask is closed, to prevent the additional air from rushing out; the flask is then detached, and hung to the arm of the balance. The flask is no longer counterpoised, but will require additional weights in the opposite scale-pan to restore it to equilibrium. If we again apply the condensing syringe to the flask, it will be found that every additional stroke of the syringe will require additional weights in the scale-pan to restore equilibrium, on account of the additional quantities of air forced into the flask.

6. Here, then, is a very clear proof that air has weight, and, in common with all heavy matter, air also possesses *inertia*, that is, it cannot be set in motion without the communication of some force; and, when in motion, it cannot be retarded or brought to rest without the opposition of force. Its inertia (like that of all other bodies) is also exactly proportional to its *weight;* and, as we have seen the latter to be very small compared with its bulk, a very small amount of

force is sufficient to impart motion to a large bulk of air; it obeys the laws of motion common to ponderable bodies, and its *momentum*, or amount of force which it is capable of exerting upon bodies opposed to it, is estimated in the same way as for solids, namely, by multiplying its weight by its velocity. The momentum of air may be illustrated by the following experiment:—Place three lighted tapers in a row at the distance of three inches apart; if we then direct an unloaded gun towards the centre taper at the distance of ten feet, and set in motion the small volume of air contained in the barrel, by discharging the percussion cap on the nipple, the flame of the centre taper will be blown out, without in the least degree disturbing the other two. Another excellent illustration of the momentum of air, and the facility with which a rotatory movement may be communicated to it, is derived from the phenomena of smoke or steam which render the motions of the air visible. When bubbles of phosphuretted hydrogen burst in a still atmosphere, each one, as it bursts, produces a beautiful ring of smoke, expanding larger and larger as it ascends. The whole circumference of each circle is in a state of rapid rotation, as shown by the arrows in Fig. 2; it being this rotation, in fact, which confines the smoke within its narrow limits, and causes the circles to be so well defined. The same phenomena may often be observed in the first puff from the chimney of a manufactory or of a steam boat, and also from the mouth of a skilful tobacco smoker. In the firing of ordnance on a still day these rings may be seen on a grand scale, and still more perfectly if the

Fig. 2.



mouth of the cannon be greased and no shot employed. In fact, any force acting suddenly upon the air from a centre imparts to it a rotatory motion.

The momentum of air is usefully employed as a mechanical force in imparting motion to windmills and ships; but it occasionally exerts itself with fearful effect in those strong winds or hurricanes, which sometimes occur in the West India Islands, where trees are torn up by the roots, buildings levelled to the ground, and the sea is driven with irresistible fury over the desolated country. Such awful calamities are caused by the momentum of the air being greater than the force by which a tree clasps the earth or a building its foundation.

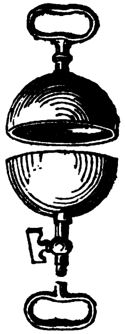
7. Another consequence of the weight of air is its *pressure*. We have already seen that 100 cubic inches of air weigh about 31 grains. It is necessary, however, in order to obtain this result, that the experiment be performed at the level of the sea; it is further necessary that at the time of the experiment the barometer should stand at 30 inches and the thermometer at 60°. But, disregarding for the present these two last conditions, let us note the change arising from difference of level only. At the level of the sea the 100 cubic inches of air contained in the flask would weigh say 31 grains. On taking this flask to the top of a mountain 20,000 feet high, the 100 cubic inches will have expanded to 200; so that, if the flask be made of some elastic material, it will have expanded to twice its former size; or, if the copper flask full of air have its stop-cock closed at the level of the sea, and opened at an elevation of 20,000 feet, exactly 100 cubic inches of air will rush out, leaving 100 cubic inches of air behind of half its former density. The reason for this is, *that at the height of* nearly 3½ miles we have ascended

above half the atmosphere, where the air in the flask has to bear only half the superincumbent pressure that it bore at the sea-level. Now it is a curious law, peculiar to gaseous matter, that its density is commonly proportional to the pressure that confines it, that is to say, by doubling this pressure we compress any air into half its former bulk (as in the above instance (4) of a diving bell under 34 feet of water); and on the other hand, on removing half the ordinary pressure from any air, it expands to twice its ordinary bulk; so that there appears no limit to the space which any quantity, however small, would fill, if relieved of all pressure. We shall return to this important law presently; but meanwhile it must not be supposed, because an elevation of 3½ miles leaves one-half of the atmosphere below us, that we should reach the limits of its existence at double that height, or 7 miles. At that height (supposing it attainable) we should still have one-fourth of the atmosphere above us, and 100 cubic inches of air from the sea-level would expand into 400, because the upper parts of the atmosphere, having less weight to bear than the lower parts, expand into far greater bulk; so that not under an elevation of 45 miles is the atmosphere supposed to be limited by the coast line of eternal space.

Thus the aerial ocean is not, like the sea, of nearly the same density throughout its depth, but gets thinner and thinner from the bottom upwards, so much so that the first 3½ miles above the earth's surface contain as much air as all the remaining 41 or 42 miles. The cause for this is, that the air at the level of the sea has to bear the weight of the whole mass of atmosphere above it, which of course acts as a powerful mechanical force in increasing the density, and consequently the pressure of the lower strata.

The pressure of the atmosphere at the sea-level can be estimated by a simple contrivance. Two hollow hemispheres of brass, Fig. 3, fitting together with smooth edges, are placed in contact; the lower hemisphere is furnished with a short tube opening into it, and this tube can be opened or closed at pleasure by means of a stop-cock. On screwing the tube into an exhausting syringe, and placing the two hemispheres together, the air can be withdrawn from the hollow sphere thus formed, and on turning the stop-cock, before removing the apparatus from the syringe, the air is prevented from entering. A handle may now be screwed to the short tube, and if two persons pull in opposite directions they will be unable to separate the hemispheres. On turning the stop-cock, however, the air rushes in, and the hemispheres fall asunder by their own weight.

Fig. 3.



Now the force which binds these two hemispheres together is the pressure of the atmosphere, which may easily be calculated by suspending them, when exhausted, by the upper handle, and adding weights to the lower handle. Suppose the sphere to be 6 inches in diameter, its section through the centre will be about 29 square inches; and, supposing the vacuum to be perfect, a weight of 420 lbs. will be required to separate the hemispheres. Now $\frac{420}{29}$ = about 14½ lbs., the amount of atmospheric pressure upon 1 square inch of surface.

There are many other methods of proving the important fact, that the weight or pressure of the air is equal to between 14 and 15 lbs. on every square inch of surface at the level of the sea; or, in other words, a column of atmospheric air one inch square, resting on any surface at the sea-level, and extending to the top of the atmosphere, weighs between 14 and 15 lbs. This will be more clearly seen when we come to speak of the barometer; but we may here anticipate the surprise of the reader who approaches this subject for the first time. He may regard such results as these as scientific curiosities, in which he is in no way concerned; but a moment's reflection will convince him that the same force which held the hollow hemispheres together, is present and active, as well for animals as for inorganic matter. If it can be proved that a column of air one inch square and about 45 miles high weighs about 15 lbs., it is evident that this pressure must be as true for a square yard, or a square mile of surface, as for a square inch; the only difference is in extent; for, if we wish to know the pressure on a square yard, or mile, we must calculate the number of square inches in such a surface, and multiply this number by 15, and the product will give the atmospheric pressure in pounds on the larger surface. But since we have seen that air is impenetrable, and that our bodies displace it, it must be evident that this pressure is also exerted on the surface of our bodies, as on that of the earth on which the air rests, the pressure of a *fluid* on any surface immersed in it being (we must remind him) exactly equal, whether the surface be horizontal, vertical, overhanging, or even facing downwards like a ceiling (see *Rudimentary Mechanics*). We dwell on the floor of an ocean of air 45 miles deep, and are as much subject to its pressure as the bodies of fishes, which inhabit the floor of the liquid ocean, are to the column of water above them. In order, therefore, to calculate the amount of atmospheric pressure on our bodies, we must ascertain the number of square inches on their surface, and multiply this number by 14½. In this way it will be found, that the atmospheric pressure upon the body of a man of ordinary stature amounts to no less than 33,600 lbs., or about 15 tons! Why, then, it may be asked, is he not crushed to death, instead of being entirely insensible of this enormous pressure? A few examples will explain this. There are many delicate and fragile animals which live at great depths in the sea, often from 2000 to 3000 feet below its surface. These creatures, therefore, have to sustain the pressure of a column of water of that height, a pressure of from 60 to 90 times greater than that of the atmosphere upon our bodies. Yet these animals are not crushed; they move about with perfect ease, under circumstances still more surprising than those under which we live. And the reason is, that this hydrostatic pressure is equal on all sides; the bodies of these animals are equally pressed above, below, and around, and the fluids within the animal are also either of similar density, or they are nearly incompressible, so that all these different pressures counterbalance each other. In the same manner the fluid atmosphere presses equally in all directions, and the human body immersed in it may be compared to a sponge plunged into deep water; it is not crushed, because the water fills the cavities of the sponge, and also surrounds it entirely. In like manner our bodies, and even our bones, are filled either with liquids capable of sustaining pressure, or with air of the same density as the external air, so that the outward is counteracted by the inward pressure. Now let us see what are the consequences of removing this pressure. Some fishes, which live at great depths in the sea, are provided with swimming bladders, or little bags full of air. On raising them to the surface, *the water pressure* is removed, and the bladder expands to such a degree as to kill the creatures instantly. In like manner, if we were raised towards the surface of our aerial ocean, our bodies would swell, and probably burst. We become painfully sensible of a partial effect of this kind, by partly removing the external pressure from a portion of the skin, as in the operation of cupping. The cupper drives out the greater portion of the air from the cupping glass, by holding it over the flame of a spirit lamp, and then suddenly claps the glass on the skin, which has been previously cut by a number of small lancets. The cup adheres by the pressure of the air on the outside, while the flesh beneath the glass, being relieved from pressure, expands, and forms a projection within the cup. The blood vessels beneath the incised portion of the skin, being also relieved from pressure, discharge their contents into the rarefied space formed in the cup.

8. We have thus far illustrated certain properties which air enjoys in common with solids, namely, *impenetrability*, *weight*, *inertia*, *momentum*, and *fluid pressure in all directions*. We have also slightly noticed its *compressibility*, and its *elasticity* when compressed. This last property requires a more extended notice, for, although common to all matter, it is so much more obvious in airs and gases as to be sometimes regarded as their distinguishing feature, and to gain for them the somewhat ambiguous title of *elastic fluids*.

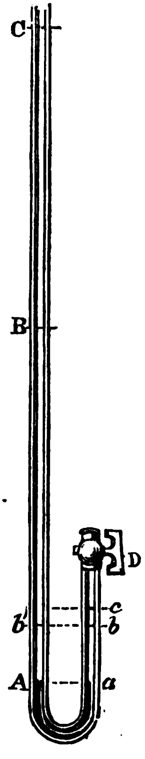
Airs and gases are so different in structure from solids and liquids, that it seems difficult to suppose them to be regulated by the same mechanical laws. The atoms or particles of solids are held together by an attractive force called *cohesion*, which differs in different solids, as is evident from the various degrees of force required to crush or grind them to powder.

In liquids the attraction of cohesion is so weak, that the particles glide over each other with the greatest ease, and instantly mould themselves to the form of the vessel in which they may be contained. Thus they would appear to have *no* cohesive force; but that they have *some* is evident by the coherence of every *drop* of water. In airs, gases, and vapours, however, this cohesive attraction is altogether absent. The gaseous particles not only have no cohesive attraction, but, on the contrary, a powerful *repulsion*, whereby they are constantly endeavouring to separate themselves as far as possible from each other. It is this repulsive force which constitutes the elasticity of aeriform bodies, of which we have now to speak.

A thin fragile vessel of any size is not crushed by the pressure of the atmosphere, on account of its perfect equability, the external pressure being exactly counterbalanced by the internal. We have only to remove one of these pressures, and we shall witness the energy with which either of these forces act when unrestrained by the other. If the neck of a square glass vessel be screwed into an exhausting syringe, and the internal air removed, it will be crushed into small fragments by the external atmospheric pressure. So, on the contrary, if a similar vessel be carefully closed at the neck and placed under the receiver of an air-pump, on removing the external pressure the vessel will be blown to pieces by the pressure or elastic force of the air inclosed within the vessel.

We see, from this last experiment, that a portion of air cut off from all communication with the atmosphere still exerts a pressure in all directions against the sides of the vessel containing it, and it can be proved that this internal pressure is exactly equal to the pressure *which an equal surface* undergoes from the weight of the external atmosphere. But this internal pressure cannot arise from the weight of the included air (for this is only a few grains); it must, therefore, arise from its elasticity, or expansive force; that is to say, the force with which it tends to expand to its natural bulk, or that bulk which it would occupy if subject to no pressure; if, for example, it were removed to the top of the atmosphere.

Fig. 4.



9. The elasticity of air and the law by which it is regulated can be very well illustrated by means of a long bent glass tube, Fig. 4, open at its longer extremity, and furnished with a stop-cock at the shorter. The stop-cock being open, a quantity of mercury is poured into the open end. The surfaces of the mercury A *a* will of course stand at the same level in both legs. The two columns of air A C and *a* D sustain a pressure equal to the weight of a column of air continued from A and *a* to the top of the atmosphere. If we now close the stop-cock D, the effect of the weight of the whole atmosphere above that point is cut off, so that the surface *a* can sustain no pressure arising from the weight of the atmosphere. Still the level of the mercury remains the same, because the elasticity of the column of air *a* D is precisely equal to the weight of the whole column before this small length was cut off. The surface A is still pressed by the whole atmospheric column, and thus we see that these two different properties of the atmosphere, its *elasticity* and its *weight*, exactly counterbalance each other.

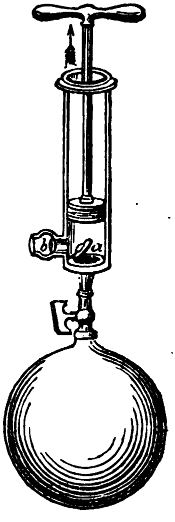
Now we know that the atmospheric pressure under ordinary circumstances is equal to 14½ lbs. on the square inch, or to a column of mercury 30 inches high. It is evident, therefore, that the atmospheric pressure acting on A is the same as would be produced by a column of mercury 30 inches high resting on the surface A. So, also, the force with which the air confined in *a* D presses by its elasticity on the surface *a* is also equal to a column of mercury 30 inches high. The pressure of the atmosphere acting on the surface A is transmitted by the mercury to the surface *a*, and balances the elastic force of the isolated column *a* D.

If we now pour an additional quantity of mercury into the open end of the tube at C, an increased pressure arising from the weight of the metal will be transmitted to the surface *a*, and will prevail over the elasticity of the confined air; the surface *a* will, therefore, rise towards D, compressing the air into smaller space. On continuing to pour in mercury until the surface *a* rise to *b*, or half way between *a* and D, that is, until the confined air is compressed into exactly half its former limits, it will be found, on drawing a horizontal line from the surface *b* to the opposite point *b′* in the longer limb, that the column of mercury *b′* B measures exactly 30 inches, the weight of which is equal to the atmospheric pressure. The force with which the surface *b* is pressed upwards towards D is, therefore, equal to *two atmospheres*, or double the force with which *a* was pressed upwards towards D. Hence it appears that the elasticity of the confined column of air, *b* D, is double its former elasticity when filling the space *a* D, so that when the air is compressed into half its volume its elasticity is doubled. If we again pour mercury into the tube at C until the air inclosed in the shorter limb be reduced to a third of its bulk, as at *c* D, the compressing force will be equal to three times the atmospheric pressure. The height of the compressing column of mercury would reach to C, namely, 60 inches above the level *c*. If we still add mercury until the column rises to the height of 90 inches above its level in the short limb, the elastic force of the confined air would be four times greater than at first, and it would be compressed to the bulk of one-fourth of its original volume.

It appears, then, that *the elastic force of air varies in exactly the same proportion as its density;* and this simple and important law, which is called, after its discoverer, the *law of Mariotte,* applies not only to air, but to all gaseous bodies when subject to such variations of pressure as can be readily commanded. Air has been allowed to expand into more than 2000 times its usual bulk, and it would have expanded still more if a greater space had been allowed. Air has also been compressed into less than a thousandth of its usual bulk, so as to become denser than water; but its elasticity has not been exactly determined at these extreme degrees, either of condensation or rarefaction, so that we have no proof that the law of Mariotte applies so extensively. On the contrary, recent experiments on the compression of gases render it nearly certain that they all vary from this law when subject to very great pressure, their density being increased in a greater ratio than their elasticity; this variation, however, is less in air than in most other gaseous bodies, and the simple law is found to apply to it very accurately when condensed as much as 50 times, and also when allowed to expand to several times its usual bulk.

10. The principle of those useful instruments, the exhausting syringe and the air-pump, depends upon

Fig. 5.



the elasticity of the air. The exhausting syringe, Fig. 5, consists of a cylinder of brass or some other metal, with a piston or plug accurately fitting it. The lower part of the cylinder contains two valves or little doors, the one opening upwards into the cylinder, and the other at the side, out into the air. The vessel to be exhausted is screwed into a short tube projecting from the cylinder. This vessel must be furnished with a stop-cock, to prevent the air from re-entering after the exhaustion is complete. Now, suppose the vessel to be screwed into the short tube, its stop-cock open and the piston at the bottom of the cylinder. Supposing we drew up the piston *instantaneously*, or in *no time*, a *vacuum* or empty space must evidently be left between the bottom of the cylinder and the piston. Consequently the air in the vessel, no longer being counterbalanced by the atmospheric pressure, expands by its elasticity, forces open the valve *a*, and fills the empty space below the piston. When the piston is drawn progressively to the top of the cylinder, no vacuum is formed, the air from the vessel expanding and following it all the way. After this the piston is forcibly driven down again, whereby the valve *a* is closed, and *b* is opened; the whole of the air in the cylinder is thus driven out through *b*, and when the piston is at the bottom of the cylinder matters are in the same state as at the commencement of the operation, except that the air in the vessel is much less dense and elastic than before. On drawing up the piston a second time, the external air cannot enter through *b*, because this valve opens outwards, and the atmospheric pressure upon it from without only serves to close it more securely. The valve *a*, however, is immediately forced open a second time by the remaining air in the vessel, which again fills the empty space that would otherwise be left by the drawing up of the piston a second time. The piston is again depressed, the valve *a* is again closed, and the air in the cylinder again forced out through *b;* and in this way the action is carried on until the air in the vessel has too little elasticity to open the valve *a*. The *exhaustion* is then said to be complete.

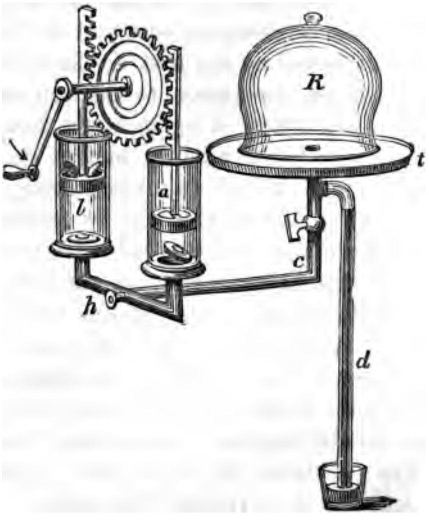
Now it is evident that a perfect vacuum or empty space cannot be formed in the vessel by this contrivance. A small portion of air must always be left in the vessel. If the cylinder be of the same capacity as the vessel, and the weight and friction of the valve be regarded as nothing, one-half of the air will pass out of the vessel by the first stroke of the piston; that is, on raising the piston to the top of the cylinder, and then depressing it again to the bottom, the vessel will be deprived of exactly half of its contents; the remaining half will still completely fill the vessel, but its atoms or particles will be farther apart, its density will be diminished one-half, and, consequently, its elasticity will be diminished in the same proportion. The second stroke of the piston will again diminish the air in the vessel by one-half; that is, the air left after the second stroke will be one-fourth of its former density and elasticity. We may carry out these results to greater length, by collecting them in a tabular form. The quantity of air in the vessel before the first stroke is to be regarded as unity.

Stroke.	Goes out.	Left in vessel.	Elastic force of the remainder.	
1st,	one half of 1	= $\frac{1}{2}$	15 inches of mercury, or 7·35 lbs.	per sq. in.
2nd,	one half of $\frac{1}{2}$	= $\frac{1}{4}$	7½ inches of mercury, or 3·675	do.
3rd,	one half of $\frac{1}{4}$	= $\frac{1}{8}$	3¾ inches of mercury, or 1·837	do.
4th,	one half of $\frac{1}{8}$	= $\frac{1}{16}$	1·875 ins. of mercury, or ·918	do.
5th,	one half of $\frac{1}{16}$	= $\frac{1}{32}$	·9375 inch of mercury, or ·459	do.
6th,	one half of $\frac{1}{32}$	= $\frac{1}{64}$	·4687 inch of mercury, or ·229	do.
7th,	one half of $\frac{1}{64}$	= $\frac{1}{128}$	·2344 inch of mercury, or ·114	do.
8th,	one half of $\frac{1}{128}$	= $\frac{1}{256}$	·1172 inch of mercury, or ·057	do.
9th,	one half of $\frac{1}{256}$	= $\frac{1}{512}$	·0586 inch of mercury, or ·028	do.

Thus, after the ninth stroke, the remaining air will only be $\frac{1}{512}$th of its original quantity; and, as it still occupies the same space, it has only $\frac{1}{512}$th the density and elastic force, which is equal to a pressure of only 0·028 lbs. to the square inch, which would scarcely be sufficient to raise the valve.

11. The air-pump, Fig. 6, is nothing more than a duplication of the exhausting syringe, with this difference, that the valve through which air is forced out of the cylinder, is not placed as at *b*, Fig. 5, but in the piston or plug itself. Two of these syringes, *a b*, or *barrels* as they are called, are arranged side by side, and the motion given to their pistons is *so managed (in*

Fig. 6.



experimental machines by a toothed wheel and racked piston rods) that, while one piston is ascending and drawing out the air, the other is descending and expelling the air already drawn out of the vessel to be exhausted. Each barrel is furnished with a valve at the bottom, opening upwards, so that, during the ascent of either piston, the air below the valve forces it open and fills the barrel. During the descent of either piston this valve is of course closed, and another valve situated in the piston itself, and opening upwards, allows the escape of the air between the bottom of the barrel and the piston. In pneumatic experiments the vessel to be exhausted, R, is called a *receiver;* it is made of stout glass, its edge is formed flat, and smeared over with pomatum before it is placed on the metal plate *t*, called the *table* of the air-pump. By this means the receiver is brought into air-tight contact with the table, and forms an inclosed chamber, in which any substance or arrangement of apparatus previously placed, may be observed under any amount of rarefaction that may be given to the inclosed air. The table is perforated at its centre with a hole, which communicates by a bent metal tube *c* with the barrels *a b*. This tube is furnished with a stop-cock, which, being closed, prevents any leakage of air into the receiver from the barrels, and, when open, allows them to act upon the inclosed air. The air is readmitted into the receiver by a perforation into the bent metal tube at *h*. This hole is closed by a thumb-screw, made air-tight by a washer of leather. One extremity of a bent glass tube *d* opens into the metal tube *c*, while the other extremity dips into a cistern of mercury. This tube, which is more than 30 inches in length, acts as a gauge, and indicates, by the ascent of the mercury within it, the amount of rarefaction in the receiver, because, as the rarefaction proceeds in the receiver, the elastic force of the air pressing upon the mercury in the gauge-tube is diminished. Indeed, with the first stroke of the pump, it immediately becomes less than the pressure of the external atmosphere on the surface of the mercury in the cistern: consequently this external pressure prevails, and forces mercury up to a certain height in the gauge-tube. As the rarefaction of the air in the receiver proceeds, its elastic force is diminished, the atmospheric pressure acts with increased effect, and the mercury rises higher and higher in the tube. The weight of the column of mercury thus raised, combined with the elastic pressure of the air remaining in the receiver, is equal to the atmospheric pressure, and it is evident that the elastic force of the air in the receiver must be equal to the excess of the atmospheric pressure above the weight of the column of mercury in the tube. If a common barometer hanging up in the room stands at 30 inches, and the mercury in the gauge at 26 inches, the difference between them, namely, 4 inches of mercury, will represent the elastic force of the air in the receiver. We have already given a rule for ascertaining how much air is left in the receiver after a certain number of strokes of the pistons of an exhaustive syringe of equal capacity with the receiver itself. It would be difficult to apply this rule to the air-pump, because it would be necessary, among other conditions, to know what relation in volume the barrels bear to the receiver; and, as receivers of all sizes are being constantly used, the calculation would be troublesome, if not impossible. If after working the pump some time the mercury in the gauge stands at 20 inches, and the barometer outside at 30 inches, then we know that $\frac{20}{30}$ths or $\frac{2}{3}$rds of the air remain in the receiver, and that $\frac{1}{3}$rd has been pumped out. But as the rarefaction of air is inversely as the quantity in a given space, if we invert the above fraction $\frac{2}{3}$ and make it $\frac{3}{2}$, then we have 1·5, which is called the rarefaction; and, in such a case, the air in the receiver is said to have been rarefied 1·5 times.

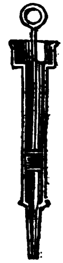
In the foregoing description of the air-pump, we have omitted many details, which, although they make it a more efficient instrument in the hands of the man of science, do not affect its principle. And it is to the principles of science, rather than to their details, that the reader should constantly strive to ascend. Facts, however curious and important, are useful in proportion as they lead to the comprehension of principles; if, therefore, our little book should be found deficient in facts, our reason for the omission is, that by thus economizing space we shall be able to extend the knowledge we are now gaining to the explanation of some of the grand operations of nature.

A treatise on Pneumatics would not, however, be considered as complete without a description of such machines as the common pump, the siphon, &c., and as such machines are capital illustrations of the pressure arising from the weight, or the elasticity, or both these important properties of the air, we must find room for a few details.

12. The term *suction* is still applied to the common pump, and to several operations and instruments of the pump kind. This term is an unfortunate one, and requires to be explained away. When we place one end of a straw in the mouth and the other end in water, and are said to *suck up* the liquid, we do no such thing. We merely draw into the mouth the portion of air confined in the tube, and then the pressure of the air which is exerted on the surface of the liquid, being no

longer balanced by the elasticity of the air in the tube, forces the liquid up into the mouth. If the straw were gradually increased in length, without increasing its whole capacity, we should find a certain length at which (however small the tube) we should not be able to raise the water into the mouth, for it would not rise more than a certain number of feet above its former level; and *no* sucking, even by the most powerful machinery instead of the mouth, could ever raise it more than 34 feet above that level, because the atmospheric pressure cannot counterbalance a column of water of a greater height than between 33 and 34 feet. And if we try to *suck up* mercury through a long tube, we shall be unable to raise it more than a few inches by the mouth, nor by the best air-pump more than about 30 inches (viz., the height at which the mercury of the barometer stands at the time), because the atmosphere cannot balance a column higher than this. Our reputed powers of suction, therefore, have nothing to do with the fluid to be raised, for that work is done by the atmospheric pressure only: we assist it or bring it into play by using the mouth as an air-pump in withdrawing the air from the tube by enlarging the cavity of the mouth or lungs. In a boy's squirt, Fig. 7, the same principle is in operation. This simple but ingenious little instrument consists of a metal cylinder drawn at one end into a point, and furnished with a plug or piston. On introducing the point into water and drawing up the plug, a vacuum would be formed below it did not the water rise and fill it by atmospheric pressure.

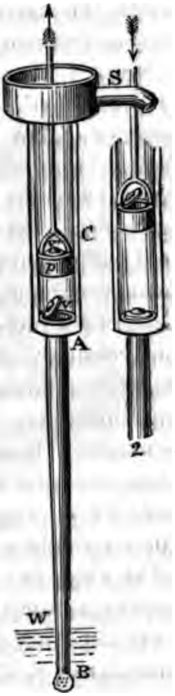
Fig. 7.



13. A similar but somewhat more complicated process is carried on in the common household pump. A long pipe A B, Fig. 8, dips at one end into the water of

a well W, the other end is furnished with a valve *v*. Above this pipe is another and wider pipe C called the *barrel*, containing a plug or piston *p*, furnished with a valve *v'* in the centre; both these valves open upwards. The piston is worked up and down by means of a lever called a *brake*. There are, however, various ways of working the piston, which of course do not affect the principle of the pump. At the commencement of the operation of pumping, the water in the well and in the pipe A B stands at the same level. On raising the piston a vacuum would be formed below it, but the air in A B by its elasticity raises the valve *v* and fills the barrel. This increased expansion of the air in A B diminishes its elasticity, so that water is forced up into A B to a certain height by the atmospheric pressure on the exposed surface of the water in the well. On depressing the piston the valve *v* is closed and the valve *v'* forced open (as in Fig. 8, 2), through which the air between *v* and the bottom of the piston escapes. On raising the piston a second time, more air rushes from A B, and the column of water in the pipe rises higher. In this way, by alternately raising and depressing the piston, all the air is drawn out of the pipe, and the column of water rises up to the valve *v*. On again raising the piston, water instead of air now opens the valve *v*, and rushes into the barrel, and, on lowering the piston, the water closes this valve *v*, thereby preventing it from again flowing back into the well. At the same time the water forces open the

Fig. 8.



valve *v*, and streams through it, so that water is now both above and below the piston. On continuing the action, the water rises higher and higher above the piston, until it reaches the spout S, where it is discharged.

Now, it is quite evident that the length of the pipe AB must have a limit; since the atmosphere by its pressure is capable of supporting a column of mercury 30 inches high, and as the specific gravity of water is about 13½ times less than that of mercury, it follows that a force which can sustain 30 inches of the heavier fluid will sustain a column of the lighter fluid 13½ times greater in height, or about 405 inches, or 34 feet instead of 30 inches. But, as the barometric column in this country oscillates between 28 and 31 inches in height, it follows that a column of water supported by the atmosphere must also be subject to a proportional variation. Besides, as the mechanism of a common pump is by no means exact, some allowance must be made for its imperfections. Hence the length of the pipe A B ought never to exceed 30 feet above the level of the water in the well. It was the lucky accident of erecting a pump over a deep well at Florence that led to the discovery of the barometer and the pressure of the atmosphere, as already narrated in a companion treatise.

14. When it is desired to raise water to a great height, advantage is taken of the elasticity of a confined portion of air condensed into a smaller space than it usually occupies under atmospheric pressure. Such is *the fire engine*, the principle of which will be understood from the section shown in Fig. 9. H is the pipe, or hose, which is prolonged to the plug, or water pipe, whence the supply of water is obtained. This pipe H communicates with two valves V V, which open into the pump barrels of two forcing pumps* A A, containing

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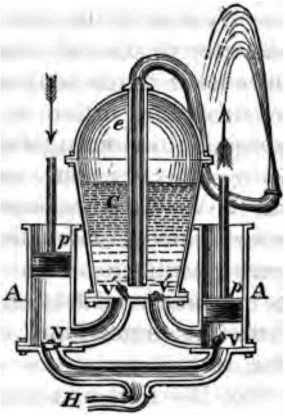
* *I.e., pumps like the exhausting syringe,* first described (10) instead of *the air-pump (11)* and common water-pump just mentioned.

solid pistons *p p*. The piston rods of these are connected with a working beam so arranged as to be worked by a number of persons on each side. From the sides of the pump barrels above the valves v v proceed force pipes which communicate with an air chamber c by means of valves v′ v′ opening upwards into it. Through the top of the air chamber descends nearly to its bottom a pipe *e*, to the upper part of which is attached the hose or jet used for directing a stream of water on the fire. By the alternate action of the pistons *p p*, water is drawn through the valves v v and propelled through the forcing valves *v′ v′* precisely as took place with the air in Fig. 8, and, when the surface of the water rises above the lower mouth of the pipe *e*, the air in the air chamber c is confined above the water; and, as the water accumulates in the air chamber, the inclosed air is compressed and acts with increased elastic force on the surface of the water, thereby forcing a column of water into the pipe *e* and out through the hose and jet attached to it with a force depending partly on the degree of condensation and partly on the elevation of the extremity of the hose above the level of the engine. The pressure of the condensed air has *first* to support a column of water, whose height is equal to the level of the end of the tube above the level of the water in the air chamber; and until the pressure of the condensed air exceeds what is necessary for this pur-

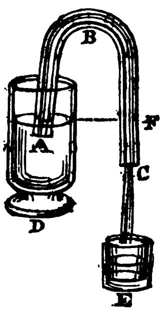
Fig. 9.



pose no water can spout from the end of the hose; and, *secondly*, the force of the jet will be proportional to the excess of the pressure of the condensed air above the weight of the column of water, whose height is equal to the elevation of the end of the hose above the level of the water in the air vessel. When the air in the air chamber is condensed into half its original bulk, it will act upon the surface of the water with double the atmospheric pressure; while, the water in the force pipe, being subject to only one atmospheric pressure, there will be an unresisted upward force equal to one atmosphere which sustains the column of water in the tube; consequently, a column will be sustained or projected to the height of 34 feet. When the air is reduced to $\frac{1}{3}$rd of its original bulk, the height of the jet will be 68 feet, and so on.

15. The siphon is not a pump, but a bent tube so contrived as to convey liquids from one vessel to another at a lower level, by raising them first *above* their natural level in the first vessel. In Fig. 10, the siphon, or bent tube A B C, has its shorter leg A B immersed in the liquid which is to be transferred from the vessel D to E. At the commencement of the operation the shorter leg is immersed in the vessel D, and the air removed from the tube by applying the mouth to the extremity C of the longer limb, or the end C may be closed and the air sucked out through an opening at the top of the bend, which is afterwards closed; or, lastly, the siphon may be held with its ends upwards, filled with liquid, the ends closed, turned downwards, and the shorter immersed in D. But in any case, however the siphon may be

Fig. 10.



filled, as soon as this is done, the atmospheric pressure on the surface of the liquid in D forces the liquid up the tube towards the highest point B, and if this point be not at a greater height than about 32 feet if water be employed in D, and not more than 30 inches if the vessel contain mercury, the fluid will pass beyond the highest point B and fill the whole of the tube to C. The vessel E can then be placed under the open end C, and the whole of the liquid in D situated above the open end A will be transferred into E.

The reader will understand why one limb of the siphon must be longer than the other by considering that, when the instrument is left to itself, the atmospheric pressure is acting as much at one extremity of the siphon as at the other. If, when the liquid column is raised to B, the mouth be withdrawn from C, the column will fall back into the vessel D. It will do the same if we get the liquid no further than F, which is the level of the liquid in D, because at that point the *upward* pressure of the atmosphere prevails over the *downward* pressure of the liquid; but beyond that point, in the direction F C, the downward pressure of the liquid prevails over the upward pressure of the atmosphere, and the liquid will flow out. Thus, the motion of the fluid is, as Mr. Webster remarks, similar to the motion of a chain hanging over a pulley. If the two parts of the chain be equal, the fluid remains at rest; and, if one end be longer than the other, it moves in the direction of the longer end. Fresh links, so to speak, are added continuously to the fluid chain by the atmospheric pressure on the surface of the fluid, so that the chain being continuous the motion is continuous also, and does not cease till one portion of the chain becomes equal to or less than the other.

A stream of water descending through the air tapers downwards, and at a certain depth divides into drops, because each particle falls with accelerated velocity, and at length (when it has overcome their cohesion) leaves the other particles behind it. But, when the stream is inclosed in a tube, this separation of its parts is prevented by the atmospheric pressure above and below keeping them together and forcing the whole stream to flow with *equal* velocity; the lower part dragging the upper after it, while the upper (by its inertia) equally retards the lower, so that they move together with the mean of their natural velocities; and the discharge is, of course, *more rapid* than if there were no tube, and will be faster the *longer* the tube. Now, as the same is true of a stream of light fluid *ascending* through a heavier, this explains why the draught of a furnace depends on the height of the chimney.

16. As the barometer is by far the most important instrument connected with Pneumatics, it is necessary to enter into the construction of this instrument and the information to be gained from it at greater length than we have hitherto done in this or in the former introductory treatise.

The essential part of a barometer is a well-formed glass tube, 33 or 34 inches long, of equal bore, containing pure mercury only, and so arranged that this mercury may be supported by atmospheric pressure; all the other appendages being contrivances for protecting the tube and ascertaining the exact height of the mercurial column.

At first sight nothing appears more easy than to fill a tube with mercury and invert its open end into a cup of the same metal. There are, however, certain practical difficulties which render the construction of *a good barometer* a work of great nicety. In the first place mercury is very liable to contamination, from the facility with which it dissolves baser and cheaper metals, such as tin, lead, zinc, and bismuth; and, as the specific gravities of these metals are all much less than that of mercury, any admixture of them will cause the height of the barometer, as indicated by a column of the adulterated metal, to be greater than in a barometer containing pure metal. There are various methods of purifying mercury, for which we must refer to chemical works*; but, in addition to these sources of impurity, it was the opinion of Sir Humphry Davy, that mercury in its pure state, when exposed to the air, absorbs both air and moisture. If such really were the case, the construction of an accurate barometer would be impossible; but, according to the experiments of the late Professor Daniell, mercury is incapable of absorbing or retaining either air or moisture; and the air-bubbles seen to rise from it when heated or when relieved of atmospheric pressure are merely retained between the mercury and the glass vessel by their attraction for the latter.

On pouring mercury into the barometer-tube and inverting it, the air thus confined between the mercury and the inner surface of the tube will be relieved from atmospheric pressure and escape into the Torricellian vacuum, where it will oppose the pressure of the external air, and constantly maintain the mercurial column at a lower level than if the Torricellian vacuum were perfect; so that the observed height of the column would not indicate the true pressure of the atmosphere, but only the excess of the pressure above that within the tube. Now, in order to get rid of this air adhering to the tube, as well as any moisture which is sure to settle upon any thing left exposed to the air, it is necessary to introduce small portions of mercury into the tube, and boil them by the action of a small charcoal fire. This, of course, requires considerable care, not only to avoid the fracture of the tube, but also to prevent fumes of mercury from escaping, for these are very pernicious if inhaled. The tube is first gently warmed, so as to dry it thoroughly. A quantity of pure mercury is then poured in, so as to occupy two or three inches of the sealed end of the tube, which is held over the fire until the mercury boils, taking care to turn the tube round upon its axis, so that the heat may be equally applied. After boiling for a minute or two, the open end is closed by a cork to prevent the introduction of moist air, and the tube is then allowed to cool, in order that the cold mercury which is next to be poured in may not crack the tube. When a second portion of mercury, which is about equal to the first, has been poured in, the part of the tube containing this new portion is held over the fire until it boils. It is again removed from the fire, and corked up as before. A third portion of mercury is then introduced, and the heat again applied to that part of the tube containing the last addition of metal; and in this way the tube is at length filled, with the exception of a small portion from which the heat has expelled the mercury. This is filled up with mercury, and the finger is now placed over the open end so as carefully to exclude any air: the tube is then reversed into a cup of pure mercury; as the column sinks, it expels the last portion of mercury which had not been boiled; and, as there is neither air nor aqueous vapour above the mercurial column, its length exactly measures the atmospheric pressure whenever the temperature is too low for the mercury to give out *any sensible quantity* of vapour. It appears, however, that mercury exists in the aeriform state whenever its temperature is above 60°, so that it must, in this state (though exceedingly rare), fill the so-called vacuum at the top of the tube, and, by its elasticity, depress the liquid and partly counter-balance the external pressure. But this source of error, which is unavoidable is fortunately extremely small.

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* See Faraday's Chemical Manipulation.

With all the above precautions, however, the barometer is liable to continual deterioration from another cause. Capillary attraction, or that force by which solids attract fluids so as to be wetted by them, does not act equally between all solids and fluids. Most solids, with the exception of certain metals, display less attraction of this kind for mercury than for any other fluid, so that they are never wetted by it, and, when immersed in it, they always retain a film of the last fluid that touched them. Hence the precautions necessary for removing the film of air from the inner surface of the barometer-tube so as to bring the mercury into contact with the glass; but as this contact cannot be insured on the *outside* of the tube, where it is immersed in the cup, a film of air is always retained at this part of the tube, and also at its under edges, which film creeps by small portions at a time into the interior, and rises up in innumerable bubbles into the vacuum, the film being constantly renewed by the descent of more air between the outside of the tube and the mercury in the cup, and in this way the outer air slowly insinuates itself into the barometer. The only means of preventing this deterioration of the barometer is, by making the bottom of the tube of some substance which attracts mercury in preference to air, so as to be wetted by the mercury. Now, as the metal platinum possesses the rare property of *welding* with glass, that is, of uniting with glass when softened by heat, it occurred to Professor Daniell to unite a ring of platinum with the open end of the barometer-tube, so as to bring it into contact with the mercury, thus effectually preventing the ingress of air into the tube.

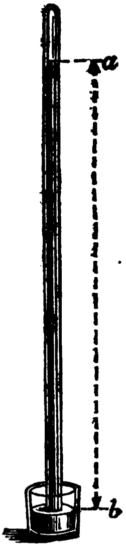
The same distinguished philosopher also invented a new mode of filling barometer-tubes, which, with far less difficulty and danger, insures as much accuracy as by the old method. The improvement consists in pouring the mercury into the tube while both are under the exhausted receiver of a good air-pump. Care is required to prevent any splashing of the mercury as it descends into the tube, for this causes bubbles of highly rarefied air to become entangled between the mercury and the glass; this, however, is prevented by pouring the mercury through a long slender funnel extending to the bottom of the tube, and dipping into a small portion of mercury previously introduced, and boiled. By this means all agitation is confined to the tube of the funnel, which, on being removed, and filling up the barometer-tube, the only part containing bubbles is that last filled; and, as these bubbles are formed by the highly rarefied air of the exhausted space, they shrink into invisible points on exposure to the common pressure, and on inverting the tube the last portion containing these bubbles is expelled, and the tube left perfectly free of air.

In making the standard barometer for the Royal Society, Professor Daniell not only followed this process, but afterwards boiled the mercury still in vacuo; and he noticed, as a striking proof of the absence of air and the perfect contact of the mercury with the glass, that, although the bore of the tube was more than half an inch, yet, on inverting it, the fluid did not at once fall to its usual height, but remained suspended to the top of the tube as water would have done in the same tube, until detached therefrom by a few concussions. Yet this fine instrument, having no platinum guard, as just described, was found after two years to grow dim (like an old looking-glass), from the insinuation of air-bubbles between the glass and the mercury, so that the tube had to be refilled as before; but, in doing so, a ring of platinum was added to the open end, which has since preserved the instrument from deterioration.

17. As the excellence of a barometer chiefly depends on the absence of all matter, except mercury from the tube, we may test its value by three indications. *First*, by the brightness of the mercurial column, and the absence of any flaw, speck, or dulness of surface; *secondly*, by the *barometric light*, as it is called, or flashes of electric light in the Torricellian vacuum, produced by the friction of the mercury against the glass, when the column is made to oscillate through an inch or two in the dark; *thirdly*, by a peculiar clicking sound, produced when the mercury is made to strike the top of the tube.

18. It has been shown, that the mercury in the tube of the barometer above the level of the mercury in the cup exactly balances the atmospheric pressure on the latter. The mean annual height of the column varies in this climate from 30·065 to 29·785 inches, and a scale is provided to measure this variation. Now, as this scale is always attached to the solid parts of the instrument, it can only measure the variations in one of the levels, namely, at the top of the column *a*, which is obviously less than the variations in the difference of level *a b*, Fig. 11, because every fall of the mercury in the tube produces a small rise of that in the cup, and *vice versâ*. It must, therefore, be remembered, that the variations in atmospheric pressure,

Fig. 11.

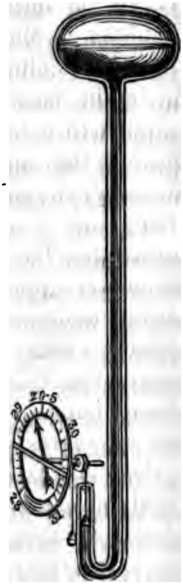


or in the height of the mercurial column, are made up of both the variations of level at *a* and at *b*, and are, therefore, rather greater than those of *a* alone, as measured by the scale. Hence the divisions of the scale should not be exact inches, but diminished, as is usually done by the instrument-makers.

19. Various contrivances have been made for increasing the length of the scale, or for making it more convenient for use. The most popular form is the common wheel-barometer, or *weather-glass*, as it is called. In this instrument, the tube, instead of terminating at the bottom in a cistern, is recurved so as to form an inverted siphon, as in Fig. 12. As a rise of the mercury in the longer or closed limb is equivalent to a fall in the shorter limb, and *vice versâ*, a float is placed on the surface of the mercury in the shorter limb, and is connected with a string passing over a pulley, and very nearly balanced by another weight on the other side of the pulley. An index hand attached to the pulley moves over the surface of a dial-plate, graduated so as to indicate the oscillations of the mercurial column. With an increase of atmospheric pressure the mercury in the longer tube rises, and that in the short tube is depressed, together with the float, and this gives a small motion of revolution to the pulley, and also the attached index hand. A fall in the longer column causes the mercury with its float in the short limb to rise, and, consequently, moves the index hand in the contrary direction.

The siphon form of barometer, as commonly made, is inferior to the cistern barometer, because a change

Fig. 12.



of pressure, such as would make a difference of nearly an inch in the upper level of the latter, would shew but half an inch in each level of the siphon; for, although the surfaces of the mercury in the longer and shorter limbs would be an inch farther apart, that inch would be compounded of a rise of half an inch at one surface, and a corresponding fall at the other. Our unit of measure, therefore, becomes only half as great, and necessarily diminishes in utility. In our figure, however, the upper end of the tube is expanded into a bulb, in order that, by enlarging the upper surface of the mercury, the difference of level may be made to depend almost entirely on the lower surface, giving the same advantage as in a common barometer with a cistern of the same horizontal area as the bulb.

20. The desire to produce a more delicate measure of the atmospheric pressure has led to the construction at various times of a *water-barometer*, the lower surface of the water being protected from direct contact with the air by a layer of some more permanent liquid, such as oil, or some elastic solid, such as India rubber. Soon after the invention of the barometer, a water-barometer was constructed by Otto Guericke (the inventor of the air-pump), and afterwards by Mariotte. It was supposed that the greater range of its oscillations would measure more minute changes of pressure. An instrument of this kind was constructed by Professor Daniell for the Royal Society. It consists of

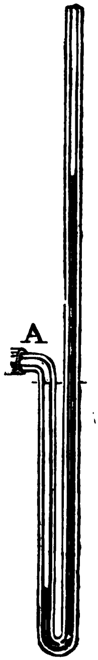
one entire tube of glass, which was drawn out to the length of forty feet without much difficulty. Its diameter is about an inch, and the average height of the fluid column 400 inches. When originally put up in the year 1832, the water in the cistern was covered with a layer of castor oil; but, as that did not prevent the admission of the outer air, it was found necessary to refill the tube. This was done in January, 1845, and a solution of caoutchouc in naphtha was substituted for the castor oil. In windy weather this barometer appears to be constantly fluctuating, indicating numerous changes of pressure, which have no sensible effect on the most delicate mercurial barometer; the column appears to be in a state of perpetual motion, compared by Professor Daniell to the slow act of respiration. But the most important result is, that this instrument precedes by one hour the mercurial barometer of half an inch bore, as this does the mountain barometer of 0·15 inch bore, by the same interval in their horary oscillations; shewing that, while philosophers are disputing about the hours of the maxima and minima, much depends upon the construction of the instrument observed.

21. There are various other barometrical instruments of greater or less utility, which have been introduced at various times for measuring the absolute pressure or elasticity of any fluid in which they are placed. We must refer to larger treatises for an account of these instruments, but we may notice the principle upon which certain instruments, called *differential barometers*, are constructed. They consist essentially of a portion of liquid placed in the bend of a siphon tube shaped like the letter U, having its two ends open to the two fluids whose pressures are to be *compared. The difference* of these pressures causes a

depression of the liquid in the leg exposed to the greater pressure, and an elevation in the other leg, the column of liquid thus sustained balancing the excess of pressure on the lower level above that on the upper. The difference of pressures is exactly measured by the difference of these levels.

Such an instrument, with mercury as the measuring fluid, forms the common *mercurial gauge* used for shewing the elasticity of steam in the boiler and other parts of a steam engine. One end of this tube A, Fig. 13, being inserted into the boiler, cylinder, or condenser, and the other end being open to the air, the rise of the mercury in the outer limb shews the excess of the elasticity of the steam above that of the external air; or, with another form of instrument, where the inner limb next the boiler is twice the length of the outer, its depression in the outer limb and its rise in the inner shews the excess of the atmospheric pressure over that of the uncondensed vapour remaining in the condenser; or over that of the low pressure steam, when such is used. In either case, as the support of 30 inches' difference of level in the mercury requires a pressure, or difference of pressures, equal to the atmospheric pressure, or about 15lbs. per square inch, the difference of pressures will always amount to about half as many pounds per square inch as there are inches between the two levels of the mercury. A scale attached to the gauge indicates the amount of pressure at a glance.

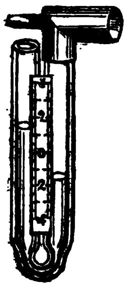
Fig. 13.



The use of steam of very high elasticity in marine, and especially in locomotive engines, requiring the extension of this instrument to an inconvenient length, has led to the substitution of *spring pressure gauges*, which, although free from the inconveniences of the mercurial gauge, are inferior in principle, because, as every spring is constantly weakened by use, the value of the scale of these instruments must be constantly changing.

22. When the difference of the pressures to be compared is very small, the difference of level in the mercury is not easily measured; all that is necessary to increase the delicacy of the instrument is to substitute a lighter liquid, such as *water*, which, being as we have seen (13) raised nearly fourteen times higher than mercury by the same pressure, renders the indications nearly fourteen times more delicate. This simple instrument, a siphon tube, Fig. 14, containing a little water, was applied by Dr. Lind as an *anemoscope*, or *wind-measurer*, one end of the siphon being bent horizontally, so as to face the wind. The two limbs of the tube were each about 9 inches long, and 4-10ths of an inch in diameter, and they were connected at their lower extremities by a smaller tube 1-10th of an inch in diameter, for the purpose of retarding the quick oscillations of the fluid by irregular blasts of wind. A scale of inches is placed between the two limbs, the zero corresponding to the level of the fluid in both tubes when subjected to equal pressures. In our figure, the two levels being each 1½ inch from zero, their difference is equal to 3 inches. It was found by this instrument, that the difference of pressures on the windward and leeward sides of any

Fig. 14.



object, even in the greatest gales, bears but a very small proportion to the whole pressure; for, while the latter is capable of supporting from 29 to 30 inches of mercury, or from 32 to 34 feet of water, the column of water supported in the wind-gauge never exceeds a few inches. While the average pressure of the air in *all* directions, therefore, amounts to 14½ or 15 lbs. on a square inch, or above 2000lbs. on a square foot, the *difference* of this pressure in different directions, produced by wind, never exceeds 15 or 20lbs. on the square foot, even in the greatest storms of our climate.

As this difference of pressures bears a simple relation to the velocity of the wind, the latter is easily calculated from it; and in this manner the following table has been constructed, to shew the velocity and the pressure on a square foot of surface corresponding to different heights of water supported in the gauge, and to different familiar designations of the intensity of wind.

Designation of wind.	*Velocity in miles per hour.*	*Inches of water supported.*	*Pressure on a square foot.*
Gentle breeze	3·25	0·01	0·83oz.
Pleasant breeze	6·5	0·04	3·33oz.
High wind	16·25	0·25	1lb. 5oz.
Storm or gale	32·5	1·	5lbs. 3oz.
Great storm	56·29	3·	15lbs. 9oz.
Hurricane	79·61	6·	31lbs. 3oz.
Tremendous hurricane	97·5	9·	46lbs. 12oz.

Hence it appears that the pressure increases as the *square* of the wind's velocity, as will be seen by comparing either of the two latter columns of the table with the second.

23. This simple and elegant instrument has, like the mercurial steam gauge, been superseded by the more

manageable but less accurate measure afforded by the compression of a spring. Machinery connected with such a spring has been made to move a pencil over paper, so as to keep a continual register of the variations in the *intensity* of wind as well as in its *direction;* and the registers so kept for the last few years have elicited some remarkable facts in meteorology, and must conduce greatly to its progress. A fine *anemometer*, or machine of this kind, is erected on the roof of the Royal Exchange, in London, and is made to register its indications in a room below.

24. There are a few other sources of error, in addition to those already mentioned, for which allowance must be made in estimating fluid pressures. One of these is the effect of *capillarity* already alluded to. In the water-barometer capillary attraction raises the water somewhat higher in the tube than is due to pressure alone, but in the mercurial column it is somewhat lower, so that in nice observations a correction has to be made for capillarity.

In a tube of small bore, when the mercury is *rising* its surface is convex; when it is *falling* it is concave, as if the centre of the fluid column always preceded the sides in all its motions; as the centre of a river or of a glacier moves faster than its sides, which are retained by friction against the banks.

Another effect is due to heat, the general tendency of which is to expand all bodies. Hence a rise in the barometric column may be due to increased atmospheric temperature, and not to increased pressure; but as this will also operate on the graduated scale, and also on the glass of the barometer tube, these different expansions may, to a certain extent, correct each other. But as solid metals, such as the scale is made of, and mercury and glass, expand unequally from the effects of temperature, it is necessary, in very nice observations, to apply certain corrections: for common purposes, however, these corrections may be neglected.

25. This leads us to the consideration of the effects of temperature upon aeriform bodies.

Under ordinary circumstances the elastic force of air varies in the same ratio as its density, *provided*, however, *that its temperature remains unchanged*. This element must always be taken into account in all comparisons of density and elasticity, because *change of temperature* in any body is necessarily attended by a change in the relations of its density and elasticity. When, therefore, it is stated that an increase of temperature produces an increase in the *bulk* of a body, or, in other words, a diminution of its density, we suppose its *elasticity* to remain unaltered, which would necessarily be the case if always confined or prevented from further expansion by the same degree of pressure, such as the common atmospheric pressure. An alteration of this pressure, however, even although amounting to its entire removal, or to its increase several times, produces so little change in the density of solids and liquids, compared with the change produced by a single degree of temperature, that these changes may be totally neglected in stating the effects of heat on those bodies. But the case is very different with gases, and we now proceed to study the simple and beautiful relations between their properties and their temperature.

26. As any *change of density* is accompanied by a similar proportional *change of elasticity* when the *temperature remains constant*, so any *changes of density* and of *temperature* are simply proportional to each other when the *elasticity remains constant*, and so also are all *changes of temperature* and of *elasticity* propor-

tional to each other when the *density remains constant.* Any one of these three elements being unchanged, the changes of the other two are proportional to each other; no one element of the three can be altered without altering *one* of the others, but it may be either one; and, when any *two* of them are constant, the third is also constant; so that, any two of them being given, the third is known.

Hence an increase of temperature does not necessarily cause bodies to expand, for this expansion may be restrained by the application of sufficient pressure; but this pressure is, in the case of solids and liquids, so great, or, in other words, their increase of elasticity is so great, for small increments of heat (supposing their bulk to remain constant), that probably no available amount of mechanical force could sensibly prevent their expansion. But the expansion of air is to some measurable extent impeded by the smallest measurable pressure; and even a change of pressure that would double its bulk may be prevented from causing any expansion, by inclosing the air in a vessel of moderate strength. But as air, however small in quantity, always fills the vessel in which it is inclosed, it is evident that no change of temperature can in this case alter its bulk except by bursting the vessel. If the vessel be strong enough to prevent this, the inclosed air, although its *density* be unaltered, must have the repulsive force of its particles, that is, its *elasticity* increased by increase of temperature; so that, if the elasticity of the external air remain unchanged, the vessel will have to bear a greater pressure on its inner than on its outer surface; and when the difference of these two pressures becomes greater than its cohesion, it will burst, as happens with an inflated bladder held near the fire. The warm air thus liberated suddenly expands, until its elasticity becomes equal to that of the surrounding cold air, although its density is less than that of the latter, so that it will ascend through it.

27. When, therefore, it is said that portions of air and of gas expand like other bodies by heat and contract by cold, it must always be remembered that this is true only when their elastic force remains unaltered. Otherwise, whatever change any degree of heating or of cooling may produce in their *bulk* when the elasticity is unaltered, the same change will it produce in their *elasticity* when their bulk is unaltered. To render the effect of expansion visible and measurable in these bodies, they must be confined in such a way that their elasticity may always balance a constant pressure, or a constant height of some liquid. To effect this requires much care and accuracy; but, from very exact experiments made in this way, the expansion of airs has been found to present the three following remarkable features:—

First. They are more expansible for a given increment of heat than either solids or liquids. For example, steel is increased in length only $\frac{1}{1050}$th, or in bulk only $\frac{1}{350}$th, by being heated 180° from the temperature of melting ice to that of boiling water. But in the case of liquids mercury expands about $\frac{1}{60}$th, water about $\frac{1}{22}$nd, and oil about $\frac{1}{13}$th of its bulk by the same increase of heat. Air, however, is expanded by the same change (its elasticity remaining constant) no less than $\frac{3}{8}$ths, so that 8 measures of air at the freezing temperature become 11 at the boiling point of water.

Secondly. That, although each solid and each liquid has its own peculiar rate of expansion, yet *all* gaseous bodies have the very same rate of expansion, namely, that above stated, which applies to all gases as well as to atmospheric air.

Thirdly. That, while all known solids and liquids expand in an *increasing* rate or with greater rapidity the more they are heated, airs on the contrary seem to preserve an *equable* rate of expansion at all temperatures, their increase of bulk, for example, being the same from 0° or zero to 100° as from 100° to 200°; and as their expansion from 32° to 212° Fahrenheit amounts to $\frac{3}{8}$ths of their bulk at 32°, it follows that every degree on this scale corresponds to a change in their bulk amounting to $\frac{1}{480}$th[*] of the bulk at 32° (supposing their elasticity unchanged); but, if their density remain constant (as when they are confined in a given space), then each degree of Fahrenheit alters their elasticity by $\frac{1}{480}$th of whatever the elasticity would be at 32°.

Hence, if the temperature of any gas be estimated from an imaginary zero 480° below the freezing point of water on Fahrenheit's scale, or 448° below Fahrenheit's zero, the temperature so reckoned will be *directly* proportional to the elasticity of the gas when its density is unchanged, or inversely proportional to the density when the elasticity is unchanged; or, when either of these two elements is constant, the other varies in the same ratio as the temperature on Fahrenheit's scale, augmented by the constant quantity 448°.

If we know the numerical measure of the density corresponding to a given elasticity at a given temperature, we can then find under any other circumstances the value of any one of these three elements when the others are given. In the case of common air these data have been measured most accurately by Dr. Prout, who found that when its temperature is 32°, and its elasticity balances the pressure of 30 inches of mercury, its density is such that 100 cubic inches of space contain 32·7958 grains troy of it.

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[*] The reader will easily perceive that this number is obtained by dividing 180 (the number of degrees between 32° and 212° Fahr.) by $\frac{3}{8}$. Recent experiments, however, assign the fraction $\frac{1}{492}$ or $\frac{1}{493}$ instead of $\frac{1}{480}$.

28. The relation of these data is different in different gases. Thus, when common air and chlorine have the same temperature and the same elasticity, the chlorine is two and a half times as dense as the air; while, on the other hand, air is more than fourteen times denser than hydrogen of the same temperature and elasticity. Hence the reason that a balloon ascends when filled with hydrogen, which is necessarily of the same elasticity as the air which presses on it. But in order to render the densities of these three gases equal, the hydrogen must have fourteen times the elasticity of the air, and this must have two and a half times the elasticity of the chlorine (supposing their temperatures equal). But in every gas the same simple relations subsist between these three properties; so that, when the temperature is reckoned from—448°, then any two of the three (*temperature*, *elasticity*, and *density*) are proportional, when the third is unchanged.

29. In order to gain clear ideas of the relations subsisting between the temperature, the elasticity, and the density of aeriform matter, it is necessary to limit our attention to a volume of air confined in a close vessel, or in a tube such as that by which the *law of Mariotte* was illustrated (9). It is obvious that these relations or laws could never have been discovered by studying the effects of heat on the atmosphere itself; but, having once established them by experiment, the natural philosopher knows by analogy that what is true on the small scale of experiment is equally true on the grand scale of nature. Experiments form a sort of index to the volume of creation; they guide us in our search by telling us what to look for; and, confiding in the constancy of nature's laws, the natural

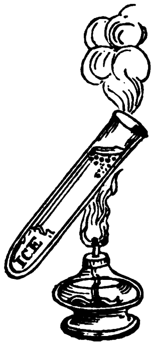
philosopher ascends from a few experiments with glass tubes and a little mercury to grand and comprehensive generalizations.

But, before we can understand the effects of heat upon the atmosphere, it is necessary to study another relation between heat and air.

30. All fluids are very bad *conductors* of heat, that is, the amount of heat which is capable of passing from particle to particle without disturbing their relative position is almost inappreciable. But the perfect fluidity and great expansive power of air renders it a most admirable *conveyer* of heat.

We may illustrate the difference between conduction and convection by comparing the action of heat on a solid with that on a liquid. If one end of an iron rod be placed in the fire, the heat will travel to the other end just as quickly whether the rod be inclined upwards or downwards. It will also travel very quickly *upwards* through a tube of water, but it will not travel *downwards*, or, if it does travel at all downwards, it will be so slowly, that a lump of ice sunk to the bottom of the tube will not be melted, although the water at the surface is boiling, as shown in Fig. 15. Hence water is called a bad *conductor* of heat; but it is a good *conveyer* of heat, as may be proved by applying the heat *below* the tube. The particles of water at the bottom immediately expand by the heat, become lighter than the parts above them, and rise up to the surface, while the cooler and consequently heavier portions descend and occupy their place; they in their turn become heated and ascend, while another set of cooler and heavier particles descend,

Fig. 15.



and thus a constant circulation of *currents* is established until the whole of the water attains the boiling point. But, when heat is applied at the surface, no such currents are established, the upper layer becoming heated without communicating much, if any, heat downwards.

31. It may be supposed that such an experiment as this does not apply to the atmosphere heated by the warm rays of the sun. It does, however, apply with the greatest strictness. The rays of the sun are not warm in passing through transparent media such as air; they give out no appreciable heat until they are arrested by some body capable of receiving them, and then, and not until then, is any warmth experienced. Even at the equator the air receives comparatively no heat from the powerful vertical rays of the sun above, but is heated almost entirely from below by the surfaces on which it rests, which are made hot by the rays which have passed through the clear air without any heating effect. This beautiful provision is necessary to give motion to those horizontal currents which produce *wind*, and those ascending and descending currents which mingle all the particles of air, and tend to preserve its purity, and to equalize the distribution of heat throughout the atmosphere. If the atmosphere were heated from above instead of from below, it would arrange itself in layers as fixed and determinate with respect to each other as those of a sedimentary rock, only increasing in density by night and expanding by day; all then would be a universal calm; there would be no cool gales from the temperate zones to mitigate the heat of the torrid or the cold of the frigid regions; the one would be desolated by heat and the other by cold, and both alike uninhabitable.

32. But as the solar rays are vertical at only one spot at a time, and become more and more oblique

as we recede from that spot, every gradation of temperature is experienced from 120° above to 50° below zero. If we suppose two spots on the earth's surface, one situated vertically under the sun, and the other receiving his rays obliquely, and consequently with less heating effect, the greater expansion of the air over the former spot will cause it to extend altogether to a greater height; but this will not influence the barometer, because, although there is a greater height of air on the warmer spot, there will be the same absolute quantity on both. But, as it is impossible for a fluid to remain thus heaped up in one spot without tending to assume a level surface, the heap of air above the warmer spot will overflow and spread over the colder, thus causing an accumulation of more air on the colder place than on the warmer, and the barometer will rise at the one place and fall at the other. But, as the lower stratum at the cold spot will thus be more elastic than that at the warm spot, the former will immediately rush into the latter until their elasticities are equalized. This motion constitutes *wind*. The equatorial regions being constantly more heated than the polar, the atmosphere above the former (independently of centrifugal force) must always extend higher than over the latter, and its upper portions must always be overflowing and tending to produce a level surface which is never attained. But this upper current *from* the equator is supplied by another current at the earth's surface, flowing with equal constancy *towards* the equator. Indeed, these contrary currents exist on a small scale in every room in which a fire is burning; but they may be best illustrated in two adjoining rooms, in one of which is a good fire, while in the other there is none. If the door between the two rooms be thrown open, the cold air will *enter the heated* room in a strong current; at the same time the heated air of the warm room ascends and passes the contrary way into the cold room at the upper part of the same doorway, while in the middle of this opening, exactly between the two currents, the air appears to have little or no motion. On holding a lighted candle near the bottom of the doorway where the air is most dense, the flame will be strongly drawn towards the heated room; and, if held near the top of the door, it will be drawn towards the cold room with somewhat less force, while midway, between the top and bottom, the flame will scarcely be disturbed. Cases of this kind are illustrations of the convection of heat, similar to that which takes place in a boiler; and a similar process is carried on in the great aerial ocean, the whole mass of which is kept in perpetual circulation by the partial application of the sun's heat. An upper current of warm air is constantly flowing from the equator towards the poles to supply the place of the lower current, which flows in the contrary direction near the earth's surface, and forms, in certain latitudes, what are called the *Trade-winds*.

33. The tendency to the equalization of elasticity and of heat in the atmosphere, or, in other words, to equality of pressure in all parts of the same horizontal stratum, and to equality of heat in all parts of the same vertical column, is the cause of all winds, however they may be modified by local circumstances. Equalization of heat, however, does not imply an equal temperature. The quantity of heat required to effect a given change of temperature in a given portion of air depends on its bulk rather than on its weight, because the specific heat or capacity of air becomes greater the more it is rarefied; so that by suddenly rarefying a portion of air its temperature is instantly lowered, and when suddenly condensed its temperature rises; the new temperature

thus acquired being, however, in each case only momentary, because the equilibrium of temperature is immediately restored by the surrounding bodies. But this change of temperature is permanent when produced by the removal of a portion of air from a denser into a rarer stratum, or *vice versâ*. Thus if a portion of the earth's surface could be transported to any height, so as to be relieved of a portion of the atmospheric pressure, its consequent diminution of *elasticity* would be more rapid than that of its *density*, because this diminished elasticity is due, not only to diminished density, but also to diminished temperature: the result is an increased capacity for heat, whereby it requires more heat than before to preserve its temperature unchanged; but it obtains no additional supply, because all the surrounding air is as cold as itself. The normal or equilibrial state of the atmosphere as regards heat is not, therefore, a state of equal temperature throughout its height, but a temperature gradually diminishing upwards, according to a simple mathematical law, the fall of temperature being equal for every equal height ascended, and on an average it is very nearly 3° of Fahrenheit for every 1000 feet.

This explains the changes of climate so beautifully exhibited in miniature on the slopes of mountains, where within a few miles are brought together those varieties of nature usually spread over many degrees of latitude. Thus on the sides of the Andes or other intertropical ridges the scenery of every zone is found, and the traveller in the course of a couple of days passes in review the whole scale of vegetation; from matted forests impervious to the sun, filled with the aroma of gums and balsams, and resounding with the din of animal life, he passes by imperceptible gradations into the peaceful woods of a temperate region, where the trees, as he continues to ascend, become smaller and less crowded; these are gradually succeeded by shrubs, low herbage, mosses, and lichens, until at length he enters upon those awful solitudes of snow, where organic life appears extinct.

34. This striking succession of changes is explicable if we bear in mind that the mean temperature of the equatorial atmosphere (which at the sea level is 82°) is diminished 1° for every 333 feet of ascent; so that at the height of 50 times 333, or 16,667 feet, the mean temperature is reduced to 32°, that is to say, it is as often below as above the freezing point; and, as there is no variety of seasons near the equator, it of course freezes every night at this elevation; so that, while there is an eternal summer in the plains, there is an eternal winter on the mountain tops. Indeed, it is found that no summit exceeding 15,700 feet is ever free from snow.

The distinct line formed by the lower boundary of the snow on mountains furnishes us with a *natural register thermometer* on a stupendous scale, as Professor Daniell appropriately names it, a scale of which each degree occupies more than 300 feet measured vertically. Except at the equator, this line of course rises in summer and falls in winter, the difference produced by seasons being increased the farther we advance towards the poles. The lowest position of the snow line depends, of course, on the winter temperature, which diminishes immediately from the equator, very slowly at first; so that this limit, which at no place within the tropics descends much below 15,000 feet, afterwards declines so much as to meet the sea-level at about the 40th degree of latitude, while, in all latitudes above this, frost and snow occur in winter, even at the sea-level. But the highest position of the *snow-line*, or that limit above which it never thaws, must of course depend on the summer temperature. This line coincides with the former only at the equator, and, instead of declining immediately therefrom, it even rises a little towards the tropics, because their *maximum* or *summer* heat exceeds the *constant* heat of the equator. Beyond these limits, however, the line of perpetual snow regularly descends, until in the central latitudes of Europe (on the Alps for example) it is reduced to 8000 feet, on the Norwegian mountains to 5000, and in the Arctic Regions it descends to the sea-level.

35. Thus we see that a certain rate of upward diminution of temperature is necessary to the atmospheric equilibrium; but this diminution of temperature produces no currents, because the upper strata, notwithstanding their coldness, have no tendency to descend, nor the lower and warm strata to ascend, because in changing their position they would also change their temperature. Currents can only be set in motion by a still greater inequality of temperature, by the lower strata becoming still warmer, and the upper still colder than the heat equilibrium requires. Now, there is a constant tendency towards such an increase of inequality, because the lower strata are constantly in the day time receiving heat from the earth or sea, made hot by the solar rays, while the upper strata are losing heat by radiation into space, the constant temperature of which is supposed to be 58° below Fahrenheit's zero.

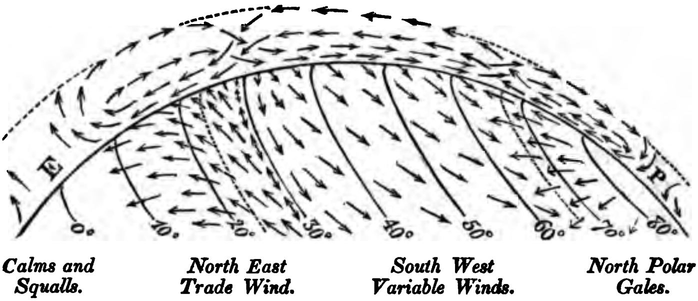
36. From this view of the atmosphere we are able to understand the wonderful and beautiful contrivance by which the winds of the temperate zones are made to mitigate the extremes of temperature, both in the tropical and the polar regions. It might be thought that the prevailing winds next the earth's surface could

not have this doubly beneficial tendency, but that they must *always* blow from the colder of two parallels into the warmer, as is the case with those currents which produce the trade winds. We must now inquire why this law is reversed in nearly all places between the latitudes of 30° and 60°, as in this country and all over Europe, for example, where the prevailing winds blow from warmer into colder latitudes. It has been already stated (32) that the immediate effect of a difference of temperature between two adjoining columns of air is to make the warmer column overtop and overflow the colder. In fact, all the upper half of the warmer column (or the half in respect of *quantity*, not *height*) is rendered denser and more elastic than the corresponding parts of the cold column; but this difference of elasticity, which is greatest at the top, diminishes downwards to a certain point where the pressures of the two columns are equal, and consequently there is no wind either way. Below this the difference is reversed, the colder column being the more elastic, and therefore flowing into the warmer more and more strongly as we descend. The trade-winds are thus accompanied by an exactly equal counter-current from the equator in the upper half of the atmosphere; the existence of such a current, exactly opposite in direction to that below, being abundantly confirmed by travellers who have ascended the peak of Teneriffe, or that of Owhyhee, the only insular mountains sufficiently high to reach the upper current. The summits of most of the West India islands, however, approach the neutral line of separation between the two currents. Indeed, the trade-winds appear to be so much diminished there as to be inappreciable above the level of 3000 feet, although the other current cannot be felt below 12,000 feet. The effects of the upper current were strikingly displayed in the volcanic eruption at St. Vincent, in 1812, the ashes of which were carried to Barbadoes; and those of Cosiguina, a volcano in central America, have been conveyed to Jamaica in direct opposition to the course of the constant trade wind. Light clouds also, which float at a greater height within the tropics than elsewhere, frequently give evidence of the same fact. Now, it is obvious that this upper current, constantly losing heat by its exposure to open space, must, after travelling a certain distance, become cold enough to descend, and change places with the lower current. This change appears to take place usually about the 30th parallel of latitude in each hemisphere, which is accordingly the outer limit of the trade-winds. Beyond this the equatorial current is undermost, and continues to be so until it again becomes by contact with the earth sufficiently warmed to resume its original position above the colder current that proceeds from the polar regions. It will of course be understood that the number of these changes that may occur between the 30th parallel and the pole will depend on difference of season, the amount of radiation from the sun and from the earth, the screening effect of clouds, and many other local circumstances, and hence the proverbial *inconstancy of the winds* over the cooler half of each hemisphere; an inconstancy arising, not from the absence of exact laws (for these winds are regulated by laws as fixed as those which apply to any other terrestrial phenomena), but from the presence of so many disturbing causes, which, as they cannot be anticipated, so they cannot be taken into account in attempting to generalize the phenomena of these winds, —a circumstance which clearly exhibits the folly of those half-informed persons who construct weather-almanacs for predicting atmospheric changes a year in advance.

The superior return current from the equator having descended at about the 30th parallel commonly continues to be the lower current or prevailing wind until it approaches the polar circle, where it again rises and is replaced by the *polar gales*, which prevail in high latitudes. These are caused by the cold and dense air of the polar regions sinking and spreading in every direction, being overflowed by an ingress of warmer air from every side, which supplies a constantly descending cataract of air upon the pole the exact converse of the effect at the equator.

These effects are embodied in one view in Fig. 16,

Fig. 16.



which represents a quadrant of the atmosphere between the pole P and the equator at E. At E the heated air ascends and forms the upper current until it reaches about the 30th parallel, where it descends and forms the lower current, which it continues to do until it approaches the polar circle, where it again rises. At the pole P the arrows are intended to represent the polar gales descending and forming the lower current. On leaving the polar circle they are displaced by the warmer return current from the equator, and, rising above this, descend at about latitude 30° and proceed to the equator, forming the constant north-east trade-wind in the northern hemisphere, and an equally constant south-east trade-wind in south latitudes.

37. But it may be said that this flow of air from the poles to the equator ought to produce a constant north wind in the northern hemisphere, and a constant south wind in the southern hemisphere, at least within a certain limited distance of the equator, probably below the latitude of 30°, or over the warmer half of the earth's surface. The reason why we do not find this to be the case is on account of the motion of the earth on its own axis from west to east. The earth being a sphere, the different parts of its surface must, of course, move with very different velocities. At the poles the motion is nothing, but at the equator it is 1042 miles an hour. In the latitude of 30° it is about 900 miles an hour, so that in the belt between the equator and latitude 30°, the average velocity may be stated at 980 miles an hour, while the space lying between 30° and 40° does not move at a greater rate than about 850 miles an hour.

Now, as the atmosphere may be regarded as an integral portion of the earth's surface moving round with it with the same velocity, it follows that the cold current of air which sets in from the temperate zones towards the equator not only has a motion north and south in that direction, but also a velocity of about 850 miles an hour due to that parallel of latitude from which it is withdrawn; the equatorial regions, however, are moving to the eastward at the average rate of 980 miles an hour; the cold air arriving into these regions at the slower rate would, on its first arrival there, be left behind; or, in other words, the surface of the earth would travel faster to the eastward than the air upon it, and this would produce an apparent or relative motion in the air from east to west, that is, an easterly wind. Thus the cold current moving towards the equator is influenced by two sources of motion; the first caused by the heat of the torrid zone producing a partial vacuum, to fill up which the cold air from the temperate zones rushes in towards the equator and at right angles to it; the second source of motion is that which has been communicated to it in a direction due east by the rotation of the earth in the temperate latitudes it has left. The resultant of these two motions is the south-east trade-wind in south latitude, and the north-east trade-wind on the northern side of the equator.

When the slower moving air of the temperate zone first arrives at the quick-moving or tropical belt of the earth, the difference of their velocities is great compared with the other motion of the cooler air towards the equator, and consequently the wind blows at the extreme edges of the trades nearly from the east point. This gradual change in the direction of the trade-winds is thus accounted for:—as the difference in velocity between each parallel and the next becomes less and less in approaching the equator, so the lagging behind of the air, which constitutes its westward tendency (or *easting* as it is called by sailors), becomes less and less. The 30th parallel, which moves at the rate of 903 miles an hour, has a less velocity by 77 miles than the 20th parallel, which moves at the rate of 980 miles an hour, while the 20th is only 46 miles an hour slower than the 10th parallel. Thus, the air in travelling from the 30th to the 20th parallel must be more retarded, or have more easting than that which travels from the 20th to the 10th parallel. As the air from the cooler regions draws near the equator, its velocity is checked by becoming heated, which gives it a tendency to rise rather than to flow along the surface; and it is further checked by the meeting of the two opposite currents, one from the north and the other from the south.

As every current towards the equator must be rendered easterly, so every current from the equator must become a westerly wind, because it proceeds from a quick moving into a slower moving latitude, and must, therefore, rotate quicker than the part of the earth on which it arrives. And as this cause operates least powerfully near the equator, and becomes more powerful in receding therefrom, this would cause the upper tropical current to become more and more westerly as it advances towards the temperate zones; thus describing the same apparent curve as the trade-winds below it, and moving everywhere in a direction exactly opposite to them,—a fact which has been established by observation. When this upper current first precipitates itself on the earth's surface, about the 30th parallel of latitude, it has lost but little of its equatorial velocity, because the only friction to which it has been subjected is that of the lower current; and hence the furious westerly gales which are so prevalent beyond the limits of the trade-winds, or about latitude 30° in each hemisphere.

38. The equatorial limit of the two trades, or the region of calms and light variable winds, is subject to continual change, depending on the position of the sun. As the circle of greatest heat does not coincide with the equator, except at the time of the equinoxes, but with a parallel to the north or south of it, it will readily be seen how the whole system of tropical winds must to a certain extent follow the sun; that is, the limits of all these winds must advance northward in

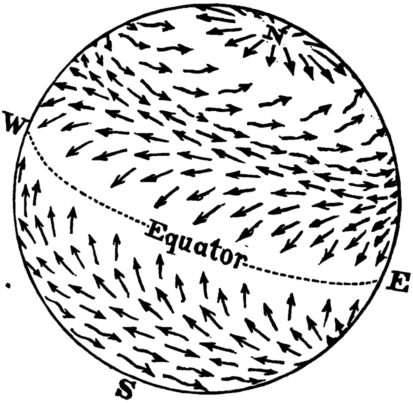
our summer, and recede southward in our winter. Hence the regions of calms and light variables is bisected by the equator only at the equinoxes. In July and August this region is wholly north of the equator, and extends as far as 12° north latitude, while in January, it is, on the contrary, almost entirely in the southern hemisphere. Thus, in our summer, the southern trade sometimes crosses the equator, and advances a degree or two to the north of it; while, in our winter, the northern trade advances nearly up to the equator, but never crosses it. The reason for this difference is the greater average amount of heat in the whole northern compared with the southern hemisphere. Indeed the line of greatest mean yearly heat is situated entirely within the northern hemisphere, nowhere approaching the equator nearer than three degrees. The phenomena of the winds are, therefore, symmetrical on each side of the line of greatest mean yearly heat rather than on that of the real equator.

39. The outer or temperate limits of each trade-wind also partake of this northward and southward shifting, because, the warmer either hemisphere may be, the farther will the upper current travel into the temperate zone before it becomes sufficiently cooled to sink and usurp the place of the lower current, which constitutes the trade-wind. Hence there are places situated about the 28th parallel in each hemisphere which have a constant east trade-wind during their hottest months only, and the above-mentioned westerly gales during the cooler part of the year.

40. The following figure, Fig. 17, will serve to show the prevailing direction of the winds or *lower* atmospheric currents at different parts of the earth's surface, apart from the effects of local peculiarities, such as sea and land breezes. The facts intended to be

impressed on the mind by this diagram are, 1st, the prevalence of *calms* within a few degrees on each side of the equator, varied, however, by frequent short squalls and light variable winds from every point; but, according to Captain Basil Hall, mostly from the south, probably on account of the general lower temperature of the southern hemisphere than the northern. 2ndly. The constancy of the trades from the 10th to the 28th degree of latitude, their directions being *polar* where they approach nearest the equator, and gradually more and more *easterly* in receding therefrom, until outside the tropics they become *east*. 3rdly. The conflict and alternate preponderance of these *east* winds and of *west* gales about the 30th parallels. 4thly. The prevalence of *easterly* and *equatorial westerly* winds from the 30th to the 60th parallels. 5thly. The prevalence of *polar* gales about the arctic and antarctic circles.

Fig. 17.



It is of course impossible, in Fig. 17, to show the upper currents*, which should theoretically blow at every spot, nearly contrary to the prevailing lower ones. Free from all the irregular disturbances of the earth's surface, these upper currents are supposed to flow with a slow but unruffled and undeviating constancy, as seen in the motions of lofty clouds, and confirmed by the experience of aeronauts. Mr. Green states, that in this country, whatever may be the direction of the wind below, within 10,000 feet above the surface of the earth its direction is invariably from some point between the north and west.

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* These will be found represented in Fig. 16.

41. We must now notice certain modifications in the trade-winds, produced by the presence of large masses of land. If the earth were a uniform mass of water or of land, these winds would blow with the utmost regularity; but, as the surface of the earth is broken very irregularly by masses of land and water, the law of the trade-winds is greatly disturbed. This is especially remarkable in Mexico and India. That part of the Pacific which extends from the Isthmus of Panama to the peninsula of California lies between 8° and 22° N. latitude. The sun's rays striking directly on the great territory of Mexico heat the land strongly, thereby causing the air over it to rise; the vacuum is filled up not only from the northward, but also by the comparatively cool air of the equatorial regions in the neighbourhood. The air coming from that part of the globe which revolves quickest to a part which moves more slowly, produces not an easterly wind, but westerly and south-westerly winds; so that the navigator is often very much embarrassed who expects east or north-east winds, according to the usual theory of the trade-wind.

The monsoons of the Indian Ocean are also modifications of the trade-winds due to the presence of vast masses of land. These winds are called *periodical,* to distinguish them from the trades which are *constant.* They blow for nearly six months of the year in one direction, and for the other six in an opposite direction. The Malays call them *mooseen,* which signifies *season.* These winds blow with the greatest regularity between Hindustan and the eastern coast of Africa. When the sun is south of the equator, from October to April, a north-east monsoon prevails; but when the sun is north of the equator, from April to October, a south-western current is established. When the sun passes the equator, and the monsoons are changing their direction, variable winds or tempests generally occur, a disturbance which is called by seamen the " breaking up of the monsoons."

The theory of the monsoons will be readily understood after the foregoing account of the trades. When the sun has great northern declination, the peninsula of Hindustan, the north of India and China being strongly heated, the quick moving air of the equator rushes to the northward, to fill up the slower moving rarefied space, and this supply of air, having not only a rapid velocity towards the east, but also a motion from the south, produces the south-west monsoon in the Indian Ocean, in the Bay of Bengal, and in the China Sea. When the sun, on the other hand, has great southern declination, the same seas are occupied by air, which, coming from regions beyond the northern tropic, has less easterly velocity than the space it is drawn into. This gives the air an easterly direction, which, combined with its proper motion towards the equator from the north, produces the north-east monsoon.

42. In addition to the grand effects of the trades and the monsoons, the heating action of the sun produces a *diurnal* interchange of air in some parts of the world, in what are called *land and sea breezes.* The ocean is but little affected by sudden changes of temperature, such as are produced by the succession of day and night, and it participates only to a certain extent in the alternating temperatures of the seasons. Such changes

become equalized over large tracts of salt water, and serve to temper the rigours of climate on coasts and in islands. The land, on the contrary, becomes rapidly heated by the sun, and as rapidly cooled in his absence. Thus, the great continents act as heaters and coolers of the atmosphere, and produce those changes in the aerial currents already noticed; and not only continents, but islands of moderate size, produce the daily alternation of land and sea breezes, so refreshing upon the coasts of hot climates. During the day the land becomes much more heated by the sun than does the adjacent water, and consequently the air resting upon the land is much more heated and rarefied than that upon the water. The cooler and denser air, therefore, flows from the water towards the land, constituting the *sea breeze*, and, displacing the warmer and lighter air over the land, forces it into a higher region, along which it flows in an upper current to seaward. At night a contrary effect takes place. After sunset the land cools much more rapidly than the water, and the air over the shore becoming cooler, and consequently heavier than that over the sea, flows towards it, and forms the *land breeze*.

The phenomena of land and sea-breezes may be well illustrated by a simple experiment. Fill a large dish with cold water, and place in the middle of it a saucer full of warm water; let the dish represent the ocean, and the saucer an island heated by the sun, and rarefying the air above it; blow out a wax taper, and if the air of the room be still, on applying it successively to every side of the saucer, the smoke will be seen moving towards it and rising over it, thus indicating the course of the air from sea to land. On reversing the experiment, by filling the saucer with cold water, and the dish with warm, the land breeze will be shown by holding the smoking wick over the edge of the saucer; the smoke will then be wafted to the warmer air over the dish.

43. In most mountain districts alternating currents may be observed in the atmosphere, which partake of much of the nature and regularity of land and sea breezes; they have been distinguished by the name of *hill and valley breezes*, and, as the subject is almost new to science, it may be interesting to give an example of these breezes *.

At Nyons, in the department of La Drôme, a wind has been known from time immemorial, under the name of *Pontias*. It is a cold wind, and rises every evening about 9 or 10 o'clock in summer, and at 6 in winter. Its first approach is from a narrow, deep, winding gorge, about two leagues in length, and extending on one side into the plains of the Rhone, near Nyons, and on the other side into a large valley, inclosed by the mountains of La Drôme. The breeze increases progressively during the night, until sunrise, when it begins to decline in intensity, and finally dies away when the ground has been warmed by the sun. This breeze is much more cold and violent in winter than in summer, and it often produces such a depression of temperature as to congeal the moisture of the atmosphere. In summer it has the effect of a fresh morning breeze. Its regularity is very remarkable, although subject to certain disturbances. Thus, during the greatest heats of summer when the short nights are not sufficient to cool the surface of the parched ground, the *Pontias* is scarcely perceptible. A similar effect is produced by a rainy or a cloudy night. Snow, on the contrary, appears greatly to favour this breeze. The effect of these variations is to limit its progress. In winter, or immediately before or after rains, it sometimes descends as far as the Rhone, a distance of seven leagues; but in summer, or during serene weather, it extends to a much shorter distance.

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* The subject has been raised into the importance which it seems to merit by M. Fournet, in the *Annales de Chimie et de Physique* for 1840.

This breeze does not exist in the upper regions of the atmosphere, nor even above the hills in the neighbourhood of Nyons, but seems to be entirely confined to the defile, at the entrance to which stands the town. It does not blow in an equal current, but is subject to certain swells at intervals of a few minutes, and these are most distinct when an east wind opposes its exit; it then escapes by irregular puffs. On ascending the defile, which leads into the upper gorge, the force of the wind diminishes in proportion to the ascent, and at length is entirely lost at a certain elevation.

In connection with this breeze is an upper compensating current, called *la Vesine*, or the *bad* wind, which, ascending the river of Eygues, passes over a defile, and is lost in a larger valley. This wind increases in violence with the heat of the day or of the season.

Thus we observe two breezes periodically opposed to each other; the one a nocturnal breeze, and the other a day breeze, blowing in opposite directions, according to the hour of the day, and developed entirely by the physical features of the locality. M. Fournet has also established the existence of hill and valley breezes in other mountain districts of France and Switzerland, caused chiefly by the asperities of the soil, producing daily an atmospheric flux and reflux, which manifests itself in ascending and descending breezes known in different places by local names.

44. There is, however, a distinction to be attended to in comparing the daily alternations of wind produced by mountains with those produced by coasts. The sea breeze is much more general and decided than the

nocturnal or land breeze, whereas, in mountain breezes, the nocturnal or hill breeze seems to be the most regular; because, although the mountain summits receive by day more and stronger sunshine than the lowlands, yet they also reflect and radiate more heat, besides being more cooled by the colder air in contact with them, so that on the whole it is doubtful whether they would generally become warmer than the plains, so as to receive a diurnal breeze from them, except in particular localities. But by night everything conspires to reduce the temperature of the summits, which, from their isolated position, radiate their heat in every direction through the clear rarefied air into boundless space, while the lowlands can only radiate their heat upwards and through a denser and less transparent air; and even that which they do radiate is often reflected back by a canopy of clouds, so that the nocturnal breeze *from* the hills must be far more general than the diurnal one *towards* them. In the case of sea and land breezes, on the contrary, although the land must always be more heated by day than the sea, thus producing the sea breeze, there is no apparent cause why the land, which is a worse radiator of heat than water, should ever become cooler than the water by night, so as to send forth a land breeze, properly so called. The winds so designated appear, therefore, to be truly not *land*, but *hill* breezes. We are not aware that they are ever felt on *flat* shores, such as Demerara, although this is one of the hottest coasts in the world, nor on the flat island of Barbadoes; but they are felt off the neighbouring island of Grenada, which is smaller, but mountainous.

45. Our space will not allow us to notice the interesting phenomena of the winds at greater length*;

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* The reader interested in the subject will find the principal phenomena

we must, however, just glance at those winds which are produced by whirls or rotatory movements in the atmosphere of greater or less extent, the winds which have hitherto engaged our attention being general or periodical winds of the nature of currents.

Rotatory disturbances in the air display a variety of phenomena which have been distinguished by various names, such as *whirlwind*, *water-spout*, *sand-spout*, *sand-pillar*, *tornado*, *white squall*, *pampero*, &c. These terms have been applied to rotatory storms of small extent. The *hurricanes* of the West Indies and the *typhoons* of the Indian seas are whirls of greatly increased extent, often extending from one to four or five hundred miles in diameter, and consisting of a revolving movement propagated from place to place, not by bodily transfer of the whole mass of air which at any moment constitutes the hurricane from one geographical point to another, but by every part of the atmosphere in its track receiving from that before it and transmitting to that after it this revolving movement.

It was formerly supposed, when accounts of hurricanes were received, as occurring at different islands on various dates, with marked differences also in the direction of the wind, that those violent storms were rectilinear in their course, and that such accounts related in most cases to different storms. Their true nature was first clearly established by Mr. Redfield of New York, and afterwards by Lieutenant-Colonel Reid, Governor of Barbadoes, by constructing charts on a

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of the winds brought together in a popular form, in a little book by the author of this work, entitled "The Tempest; or, an Account of the Nature, Properties, Dangers, and Uses of Wind in various Parts of the World." Published under the direction of the Committee of General Literature and Education, appointed by the Society for Promoting Christian Knowledge.

large scale of some of the most remarkable hurricanes on record. In this way a single storm was traced successively from one island or locality to another, and the direction of the wind at any one point or place was found to have no connection with the general progress or direction of the storm. For example, one of the tracks thus laid down is that of the memorable gale of August, 1830, which passing close by the Windward Islands, visited St. Thomas's on the 12th; was near Turk's Island on the 13th; at the Bahamas on the 14th; on the Gulf and coast of Florida on the 15th; along the coast of Georgia and the Carolinas on the 16th; off Virginia, Maryland, New Jersey, and New York on the 17th; off George's Bank and Cape Sable on the 18th; and over the Porpoise and Newfoundland Banks on the 19th of the same month, having occupied about seven days in its ascertained course from near the Windward Islands, a distance of more than 3000 miles, the rate of its progress being equal to 18 miles an hour. Now, the actual velocity of the wind in its rotatory movement is probably five times greater than this rate of progress, which would be equal in a rectilinear course to about 15,000 miles; but the whole length of the track does not exceed 3000 miles: we thus have strong evidence of the rotatory nature of these storms; for, if the wind move 90 miles an hour, and the whirls or eddies which constitute the storm move in a body at the rate of only 18 miles an hour, it is clear that the motion of the wind must be in circles. It is curious also that these eddies turn in a direction contrary to the sun's apparent daily motion, and, therefore, in our hemisphere, contrary to the motion of the hands of a watch, but similar to that motion in the southern hemisphere, a result which would naturally be expected from their common origin, just as two wheels set in motion by anything passing between them must necessarily turn in contrary directions. The general progress of these storms is always away from the equator, and therefore reversed in the two hemispheres; but in both they have first a westward motion, until they escape the influence of the easterly trade winds, when they turn round in a hyperbolic curve and are drifted eastward by the prevailing westerly winds of each temperate zone. Throughout their course they increase in size, but diminish in intensity, until they are lost in the winds of high latitudes, the variable and fluctuating nature of which they greatly increase.

Sir John Herschel explains the origin of one of these rotatory storms by supposing a column of air, intensely heated at a particular point of the intertropical plains of America, to rise bodily from the lower stratum of the atmosphere with sufficient ascensional force to carry it into the upper current, but retaining the full westerly energy which it has derived from the earth's rotation. Now nothing is more likely than that a *ripple* in its course should thus be produced, and that the portion thus driven upwards should, on its return, strike down far below, into the lower current. All the conditions necessary for a rotatory storm would then arise. A mass of air, animated with immense velocity, has to force its way through an atmosphere either at rest or moving in a contrary direction: a state of things which, in the movements of fluids, is invariably accompanied with vortices on one or both sides of the moving mass, which continue to subsist and to wander over great tracks long after the original impulse is withdrawn. In such vortices the motions of translation and rotation may have any proportion; but the former is usually slow compared with the latter. An illustration of this kind may be witnessed at a mill-dam when the sluice is closed so as to allow the water to escape at some small hole. A funnel-shaped depression will appear on the surface, in which air descends, often to the actual hole of escape, though many feet below the surface, but often also as an interrupted column. All the movements of a rotatory storm are here represented by the revolving fluid. So long as the hole is kept open it retains a fixed position, at least at the lower extremity, fluctuating only by a bend of the column. But if the hole be closed, it immediately begins to wander, continuing often a long time, but gradually retreating upwards.

46. It must be obvious that all these atmospheric currents, depending as they do entirely on the variations of elasticity brought about in different parts of the atmosphere by the solar heat, must be most intimately connected with the indications of the barometer. As the tendency of all these currents is to establish equality of pressure over the earth's surface, it was formerly supposed that the *mean* height of the barometric column would be found equal in every part of the world. Numerous careful and long-continued registers of its height, however, kept at various spots distant from each other, have shown a decided though very small local variation of this element, and the dependence of this variation on the latitude we will now endeavour to explain.

The atmospheric pressure is greatest at, or at a short distance beyond, the tropics, or about the outer limit of the trade winds, where the mean height of the barometer is about 30 inches. From this point it declines both towards the equator, where it is about 29·9, and also towards high latitudes. In England, for example, it is reduced to 29·8, and it continues to fall at about the same rate to the highest latitudes that have been reached. But towards the South Pole, as appears from the late expedition under Ross, the fall appears to increase rapidly, so much so, that in the Antarctic regions the mean pressure is reduced even below 29 inches; but it must be remembered that this is only the mean of three *summers*, and may possibly be compensated by increased pressure in *winter*.

The maximum of mean pressure occurring just outside the tropics, is referred by Professor Daniell, with great probability, to the obstruction caused by the meeting and crossing of the two main currents as already described (37), which must produce an accumulation of air upon that parallel where it occurs.

47. But the mean local pressure appears to depend less on latitude than on the proximity of great masses of land or water, it being highest in the interior of continents and lowest on the Pacific. Captain King, in a voyage on that hemisphere of waters, having observed the barometer five times a day for five months, obtained a mean of only 29·462 inches. Connected with this fact is the lower mean pressure in the Antarctic regions than in the Arctic, and also the well-known fact of the barometer on the borders of continents (as in this country) standing lowest during moist winds, or those which come from the ocean, and highest during the dry winds from the continent.

48. This brings us to the fact, that the local differences between the mean pressure observed at the most distant parts of the globe are very trifling compared with the variations constantly occurring at most places, indeed all places, outside the tropics. Thus in this country we have at the sea-level the mercury not unfrequently rising to 30·5 inches and sometimes falling to 28·5. This difference of two inches indicates a difference of about a pound per square inch in the

atmospheric pressure, so that we need not wonder that delicate persons *feel* the change, when the pressure on their body is increased or diminished in this manner by a few hundredweights.

These fluctuations in the barometer are by no means of equal extent in different places. Their amount increases greatly with the latitude, being much greater at St. Petersburgh or Stockholm than in London, while in warm latitudes it is greatly diminished, and within the tropics becomes not only so small as to escape the notice of unscientific persons, but assumes a totally different character from that which it has in cold and temperate climates. This difference we will proceed to explain.

49. The fluctuations occurring in extra-tropical latitudes are so fitful as utterly to defy all attempts to reduce them to rule, that is, to any periodical order. Indeed, this must be obvious from their generally acknowledged connection with the wind and weather, the uncertainty of which are proverbial. But in the torrid zone, where this uncertainty, as regards two elements at least, namely, *wind* and *temperature*, is replaced by the most clock-like regularity, the barometric changes, although so small as to be scarcely perceptible to an indifferent observer, partake of the same perfect regularity. Unaffected by the utmost extremes of wet or dry, it gives no indications of the approach of the equinoctial deluges, or the solstitial drought; it is thrown aside by the planter as a useless instrument, nevertheless its small daily oscillations go on with the regularity of a clock. Scarcely once in a man's life, at any one spot, does the mercury undergo a decided disturbance, and that not greater than occurs in England before a slight thunder-shower, but such a disturbance is the sure and rapid precursor of one of these stu-

pendous atmospheric convulsions, which, in the extent of their disastrous effects, are scarcely exceeded by the greatest earthquakes. The importance of observing the barometer at sea, within the tropics, cannot be over-rated. There are many instances recorded of ships saved from otherwise certain wreck, by the rapid fall of the mercury giving notice of an approaching hurricane.

But to return to the ordinary oscillations; it is found that, totally unconnected with changes of weather, these oscillations occur like the tides of the ocean, twice in every twenty-four hours, only with this difference, that they are purely *solar* tides, or those arising from the action of the sun only, not *soli-lunar*, or those arising from the combined action of the sun and moon. They have no variations of *spring* and *neap*, and instead of their rise and fall occupying half a *lunar* day*, it occupies only twelve hours, or half an ordinary solar day, the two maxima of pressure always occurring at the same hours, namely, at 9 o'clock, A.M., and the two minima each at about 3 o'clock, P.M. This is, therefore, a tide not produced by gravitation, for if it were, the sun's effect would, as in the oceanic tides, be masked by the greater effect of the moon; but being dependent solely on the sun's position, this atmospheric tide must be due not to his attraction, but to his heat. The manner in which this power acts so as to produce *two* opposite and equal protuberances of the atmosphere, is beset with difficulties, and cannot yet be said to be even partially understood, but the facts are nevertheless of the greatest interest to science.

50. In speaking of the *semi-diurnal* oscillations, we must always be understood to refer to what takes place at the level of the sea, because on an eminence their effect is necessarily partly disguised by the super-addi-

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* The mean length of the lunar day is $24^h\ 50'\ 21''$.

tion of that *diurnal* oscillation deduced above, the period of which being 24 hours, it must have the effect of making these 12-hour tides appear alternately unequal, and this inequality is greater the higher we ascend.

The extent of the semi-diurnal oscillation is found to be greatest at the equator, where it averages more than $\frac{1}{10}$th of an inch, and it diminishes to $\frac{6}{100}$ths of an inch in lat. 30°; being, however, in both situations greater in the hottest months than in the coolest. Beyond the limits of the trade winds, these oscillations being still further diminished, are exceeded in extent (and therefore entirely masked) by the *irregular* fluctuations so familiar in our climate. These fitful variations, unknown within the tropics, increase prodigiously in extent as we recede therefrom; and as the *regular* oscillations, on the contrary, diminish, they are of course soon lost in, or confounded with, these *irregular* ones.

51. But although thus disguised so as to be no longer recognisable by simple observation, this regular tide still flows and ebbs amidst all the irregularities of the pressure in temperate climates. The proof of this is simple and elegant. We have only to examine a barometric register kept at stated hours (at least twice a day) for a long period, to take the average of each set of observations made at the *same hour*, and by comparing these averages, it is found that the mean height at about 9 o'clock, A.M., is greater, and that at about 3 o'clock, P.M., less than at any other hour. In this climate, and in summer, the mean of a few weeks is sufficient to elicit this fact. In winter, or in higher latitudes, the greater extent of the irregular fluctuations requires a longer series to enable them to neutralize each other. In this way it is found that, however dis-

guised by irregular disturbances, the regular atmospheric tide still obtains throughout the temperate zones, although greatly diminishing in extent from the tropics to the Polar circles, near which it becomes altogether imperceptible. Among the many theories proposed to account for these oscillations, that of Professor Daniell is the most satisfactory. It is too complex to be introduced here, but we may observe that he deduced from it not only the entire disappearance of these tides at a certain latitude far short of the Pole, as above stated, but also that in higher latitudes a much smaller tide ought to appear at exactly the contrary hours, that is, flowing from 9 to 3, and ebbing from 3 to 9, and an examination of the register kept for this purpose in Captain Parry's Second Arctic Expedition, has actually given such a result, although its amount is so very small, only a thousandth of an inch, that considering the great extent of the irregular fluctuations, it is very doubtful whether the observations were contiued long enough to give a fair average.

52. This principle of obtaining the mean of many observations made under circumstances bearing a certain resemblance, and comparing this mean with the mean of many others made without that particular resemblance, is the key-stone of the meteorological arch, the sole method of accumulating that mass of materials by which the infant science of meteorology is to be nourished. It is only by such averages that the diurnal tide, observable only on eminences (50), can be shown to exist. Professor Daniell elicited it from the mean of a very moderate number of observations, even on so small an elevation as Box Hill, in Surrey, and the registers kept at greater heights show it distinctly, provided they be on narrow summits or ridges; but on extensive table lands it is not observable, because the

air resting on them has not time to flow off during the night, nor the surrounding air to overflow them during the day. This alternate flux and reflux, however, produces at the border of all elevated tracts the hill and valley breezes already noticed (43), namely, a breeze *from* the hills during the night, and *towards* them during the day, similar in character to the land and sea-breezes, and like them most observable in low latitudes, because the daily and nightly alternations of temperature are there greatest.

53. The observations on Box Hill just noticed, also displayed another oscillation, which, from the time of Newton, had often been sought for in vain, namely, the atmospheric *tides*, strictly so called, produced by lunar attraction. It is obvious that such tides, however great, could never affect the height of the barometer at the sea-level, because the greater height of air accumulated under the moon would, on the whole, weigh no more than the shorter column elsewhere, because every particle of the former column (and also of the mercury weighing it) has its weight diminished by the moon's attraction opposing that of the earth. But the effect ought to be seen by the upward diminution of pressure being *slower* under the moon; and, accordingly, the mean of several observations made when the moon was near the meridian, gave a less difference between the pressures at the foot and top of the hill than was obtained from the mean of several others made when the moon was near the horizon. It is to be regretted that similar observations have not been made at greater elevations, as they have an important bearing on the use of the barometer for measuring heights. This subject will be noticed presently (56), but we must first make a few remarks on the use of the barometer as a *weather-glass.*

54. This instrument could not have been long observed before the discovery that its fluctuations had some unknown connections with the changes of the weather in temperate climates, especially as regards wind and rain; a high state of the mercurial column generally occurring in the finest or calmest weather, and a depression of it during rain and storms. Hence, by a too hasty generalization, it was supposed that the fineness of the weather was exactly proportional to the atmospheric pressure, and, accordingly, such words as "fair," "changeable," "rain," &c., were engraved on the scale, which words have only served the purpose of bringing a really invaluable instrument into disrepute, by making it promise that which it is incapable of foretelling.

The reason why the atmospheric pressure is generally greater in dry situations, and in dry states of the weather than in moist ones, is still very obscurely known. We cannot even touch upon it in this place, because its consideration would require on the part of the reader a knowledge of the laws respecting vapour, and we prefer that he should gain from this little book a tolerably complete knowledge of the barometer, than an imperfect idea of the barometer and the hygrometer; but we may observe that a due attention to both these instruments will lead to more accurate predictions respecting the weather than can be obtained by the use of either of them singly. Indeed, the barometer used alone has, as we have endeavoured to show, a far more direct application to the theory of winds than to that of rain. Its application to the latter is only indirect, and far from being understood theoretically; still, however, the average of a large number of observations made at different times, and in different places, has furnished rules which deserve some degree of reliance.

The most important fact to be remembered is, that the state of the weather to be expected is not so much connected with the absolute height of the column as with its *motion*, whether *rising or falling*. In order to observe this most important fact an upright barometer is necessary, since the upper surface of the mercury cannot be seen in a wheel barometer. If the mercury have a convex surface the column is rising; if it is concave it is falling; when it is flat it is generally changing from one of these states into the other (24).

A fall in the mercury generally indicates approaching rain, high winds, or a thunder-storm; but it is remarkable that snow is more frequently preceded by a rise than by a fall. With this exception, however, a rising state of the mercury commonly indicates the approach of fine weather. A very high wind, especially from the S.W., whether accompanied by rain or not, is perhaps connected with the lowest state of the barometer. In England a N.E. wind is more conducive to a high state of the mercury than any other.

When the mercury rises or falls steadily for two or three days together, it is generally found that rather a long continuance of settled weather will follow; rainy in the latter case, and fine and dry in the former. By the same rule frequent fluctuations in the height of the column are found to coincide with unsettled weather.

55. Many persons are fond of entering the height of their barometers in a register once or twice a day for years together, and make no further use of these registers than to exhibit them to their friends as curiosities, and point out a remarkably low state of the

barometer at one period, and contrast this with a remarkably high state at another period. It may be thought a harsh word, but it is a fact that, as far as science is concerned, these registers are no better than waste paper; whereas they might be made of inestimable value by taking out the *monthly* and *annual means*, and sending them for publication to some local newspaper, or to any scientific journal of repute. Persons who have a tolerably good instrument, and the leisure and inclination for these observations, should make their entries at the proper hours of the day, and these are indicated by the instrument itself (49, 51). The maximum height of the column is about 9 o'clock A.M., the mean at 12, and the minimum at 3 P.M. If a person can afford time to make three observations every day, he should select these hours. If he can only make two observations, the proper periods are the very convenient hours of 9 A.M. and 9 P.M. If he can make only one observation, *noon* is the time. Professor Daniell remarks, that those who merely consult the barometer as a weather-glass would find it an advantage to attend to the three above-mentioned periods, for he has noticed that by much the safest prognostications for this instrument may be formed from observing when the mercury is inclined to move contrary to its periodical course. If the column rise between 9 A.M. and 3 P.M. it indicates fine weather, if it fall from 3 to 9 rain may be expected.

56. The *measurement of heights* was the first useful purpose to which the barometer was proposed to be applied, preceding even its application as a weather-glass; and, in this respect, it is certainly more to be depended on than any predictions as to the weather, made from it even for only a few hours in advance. This application was suggested by the results of ex-

periments performed by Torricelli and Pascal, that the mercurial column diminished in height on ascending above the level of the sea. But, at the outset of this inquiry, Pascal fell into a great error by supposing the atmosphere to be of equal density throughout, and that as the whole atmospheric column supported about 30 inches of mercury, all that was necessary was to observe the depression of the mercury on ascending a mountain, and then, by comparing the relative weights of mercury and air*, to ascertain the height of the mountain. The error, however, was soon discovered. Halley showed that the density of air decreases in a geometrical progression, while the elevation increases in an arithmetical progression; that is, if at a certain height the density was half that at the earth's surface, it would be *one-fourth* at twice that height; *one-eighth* at thrice that height, and so on; and Mariotte, about the same time, having determined that the pressure of aerial fluids is exactly proportional to their density when the temperature is equal (9), it was clearly proved by Halley that the ratio of decrease in the pressure was different from that of the increase in the heights. Indeed, if the upward diminution of the temperature be equal for equal ascents (34), it may be shown, for heights which are in arithmetical progression, that the elasticity diminishes in geometrical progression like the density, but rather more rapidly.

Now, the relation between an arithmetical and a geometrical progression, is the same as that between a series of logarithms and their natural numbers; and it occurred to Halley to apply a common table of logarithms to the solution of these questions. It was necessary, however, to fix the unit of his two series, which he did by calculating that the height at which the atmospheric pressure is exactly half that at the earth's surface, must be about 3½ inches. That is to say, although the atmosphere may extend to the height of 45 miles, yet its *lower half* is so compressed as to occupy only 3½ miles, so greatly do the upper portions expand when relieved from pressure.

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* This has been determined by Biot and Arago, to be 10.466 to 1.

Hence at the height of	3½ miles,	7 miles,	10½ miles,	14 miles,	&c.,
the elasticity of the atmosphere is	$\frac{1}{2}$,	$\frac{1}{4}$th,	$\frac{1}{8}$th,	$\frac{1}{16}$th,	&c.

Halley was induced, by certain mathematical considerations, to fix upon the number 62,170 as a constant multiplier, and the rule for the measurement of heights may be stated as follows:—Observe the height of the barometer at the earth's surface, and then at the top of the mountain, or other elevated station; take the logarithms of those numbers, and subtract the smaller from the greater; multiply the difference by 62,170, and the result is the height in English feet. This process gives a very near approximation, especially in temperate climates.

But the progress of science soon rendered it evident that a correction for temperature was necessary in barometrical measurements, and a formula has been contrived to meet most of the difficulties of the question. The following rule will be found of easy application:—Multiply the difference of the logarithms of the two heights by the barometer, by 63,946; the result is the elevation in English feet. Then, in order to correct for temperature, take the mean of the temperature at the two elevations; if that be 69.68° Fahr. no correction is necessary; if above that quantity, add $\frac{1}{480}$th to the whole height found for each degree above 69.68°; if below, subtract the same quantity. For example:—Humboldt found that at the level of the sea, near the foot of Chimborazo, the barometer stood at exactly 30 inches, while at the summit of the mountain it was only 14.85. The logarithm of 30 is 1.4771213, and the logarithm of 14.85 is 1.1717237; then subtracting

$$\begin{array}{r} 1.4771213 \\ 1.1717237 \\ \hline 0.3053976 \end{array}$$

Multiply this by 63,946, which produces 19,539 for the elevation in feet. If the mean temperature of the two stations were 69.68° no correction is necessary for temperature. This is a tolerably close approximation: the most careful calculation has given 19,332 for the real height, and this was probably estimated for a lower temperature.

A method has been given by Leslie for measuring heights without the use of logarithms. This rule is as follows:—Note the exact barometric pressure at the base and at the summit of the elevation, and then make the following proportion:—As the sum of the two pressures is to their difference, so is the constant number 52,000 feet to the answer required in feet. Suppose for example the two pressures were 29.48 and 26.36; then

As $29.48 + 26.36 : 29.48 - 26.36 :: 52000$ ft. : 2905.4 ft., the answer required.

This rule has been found applicable to the mean temperature of our climate for all heights under 5000 feet, and is, therefore, available for all the elevations in Britain. The barometer should be furnished with a vernier, for reading off hundredths of an inch, as a difference of $\frac{1}{10}$th of an inch will indicate from 88 to 100 or 110 feet, according to the density or pressure.

Of course the results are not perfectly but only approximatively true.

57. The frontispiece to this treatise contains a scale of the most remarkable heights and depths, compared with the probable height of the atmosphere. The horizontal lines show the heights to which a barometer must be carried to make the mercury sink to the number of inches indicated in the right-hand column. Thus, supposing the pressure at the sea-level to be equivalent to 30 inches of mercury, at the height of two miles (as shown on the left-hand scale) the pressure will be reduced to about 20 inches (as seen by the right-hand scale), showing that at this height the barometer is relieved of ⅓rd of the ordinary pressure, or, in other words, that ⅓rd of the whole mass of air is situated below this level. It will be seen also that at five miles (which is about the height of the highest peaks of the Andes and Himalaya) the pressure is only equivalent to 11 inches; and at 5½ miles to about 10 inches; so that only ⅓rd of the atmosphere (as regards quantity) is situated above that level. The lines marked 10 and 20 inches, therefore, divide the whole atmosphere into three layers, containing equal quantities of air; and, by the same reasoning, it will appear that all the horizontal lines in the figure divide it into 30 layers of equal mass, so that their extreme inequality of space will give a correct idea of the enormous compression of the lower strata by the weight of the upper; the upper 30th part, for instance, occupying more space than all the remaining $\frac{29}{30}$ths. The plane which divides the atmosphere into two equal halves (or which is marked 15 inches in our figure) will be observed to be at the height of about 3½ miles, or 18,000 feet. Humboldt and Bonpland ascended on the side of Chimborazo a little above this level; and in

balloons the barometer has sunk sometimes to 12 inches, showing that the aeronauts had risen above $\frac{3}{5}$ths of the atmosphere.

By applying a pair of compasses to the right-hand scale, it will be found that the distance from the 30 to the 15 inch level is the same as from the 20 to the 10 inch, from the 10 to the 5, from the 2 to the 1, from the 4 to the 2, or from any other number to its half or double. So also the distance between any number and its triple is the same as between any other number and its triple; and the same is true of any other multiple: the distance between 30 and 6, for instance, is equal to that between 20 and 4, between 15 and 3, or 5 and 1. Now, this is the property of a *logarithmic scale* (such as that engraved on the carpenter's sliding rule), viz., that numbers having equal ratios are found at equal distances apart; just as in a table of logarithms, any pairs of natural numbers that have equal *ratios* are found opposite to pairs of logarithms that have equal *differences*, so that numbers in geometrical progression have their logarithms in arithmetical progression.

This law, then, that the elasticity of the air diminishes upwards in a geometrical progression, for heights that increase in arithmetical progression; or that the pressures at different heights vary as the numbers of which those heights are the logarithms, is the foundation of the method of measuring heights by the barometer. This law, although preserved at the greatest accessible heights, cannot remain true throughout the atmosphere, because in such case it could have no limit, for there would be no height at which the pressure could be reduced absolutely to 0, so that air in an inconceivably rarefied state would extend even to the moon and the planets, which is certainly not the case; and indeed various reasons lead to the conclusion that it ceases altogether under the height of 100, and, in all probability, under 50 miles *. Even at 20 miles, it must be rarer than the *vacuum* produced by the best air-pump, and at 5 miles probably too thin to support animal life.

58. In addition to the aerial currents of varying degrees of intensity, which constitute all the varieties of wind, there are other movements carried on conjointly with the former, not less important to us, and even more wonderful. These are the vibratory motions by which sound is propagated; and there is something very astonishing in the precision and distinctive character of these aerial pulses. Amidst the multiplicity of sounds which fill the air there is no difficulty in naming the source of each. The ringing of bells, the hum of insects, the song of birds, the lowing of cattle, the rattle of cart-wheels, the roar of the cataract, and the rolling of thunder; all these and a thousand other sounds are, as it were, daguerreotyped in the air, and represent to us their source with characteristic distinctness. They do not confuse or bewilder us, for although apparently mingled together, we can separate them and attend to any one; we can lay that down and attend to another; and what is perhaps of far greater consequence, we can recognise our friends and acquaintances by the sounds

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* Calculations founded on the duration and appearances of *twilight* (a phenomenon due entirely to the atmosphere) give for its height values varying from 45 to 90 miles. No certain conclusion can, therefore, be drawn from these; but by a different calculation, depending on a more careful collation of the observations made on the Andes and in balloons respecting the upward decrease of temperature and pressure, M. Biot has been led to infer that the elasticity and density become 0 at a height not exceeding 30 miles. Other philosophers calculate the height at from 40 to 50 miles. The phenomena of twilight may also be accounted for without supposing so great a height as 45 miles, which is therefore more probably above than below the truth.

of their voices alone, for no two friends have the same voice, any more than the same countenance. And then how wonderful is the power we possess of shaping air into words, by which we express our thoughts, our wants, our instructions, our promises, our affections to others, by which we regulate the actions and influence the judgment of others. All this is very wonderful, and science can take us a very little way indeed in explaining the *timbre* or characteristic qualities of different sounds. We have also no means of measuring the different intensities of sounds. We have numerous instruments for measuring the effects of heat, electricity, atmospheric pressure and vapour; but we have no *Sonometer* for measuring the intensity of sound, because we do not know what effect of sound can be taken as the true measure of its intensity. A similar objection applies to *Photometers*, or *light-measurers.*

The conditions necessary to the production and propagation of sound were noticed in a former treatise*. A body in a state of stable equilibrium is disturbed therefrom by a certain impulse. It should here be remarked, that mechanicians distinguish two kinds of equilibrium, *stable* and *unstable*. Both alike are produced by the marked neutralization of different forces, but with this difference—that if a body in unstable equilibrium be moved ever so little, so as to leave a portion of force unbalanced, this force will urge the body further and further from its original position, and it will not rest until it has found a new position of equilibrium. But a body in stable equilibrium not only tends to preserve its position unaltered, but to return thereto when disturbed within certain limits, because the force thus brought into activity does not tend to drive it farther, but to bring it back to its former position. But the momentum thus acquired will not allow it to stop here. It will (if we disregard all loss of momentum by its transference to other bodies) proceed as far beyond the position of equilibrium as it was disturbed therefrom at first, and will thus continue to *vibrate* or oscillate through an equal space on each side of the position of equilibrium. And it would do so for ever, were it not for the action of what are called *retarding forces* or *resistances*, such as *friction*, *resistance of the air*, &c.; or, in other words, the motion is shared among gradually increasing quantities of matter until its intensity becomes inappreciably small.

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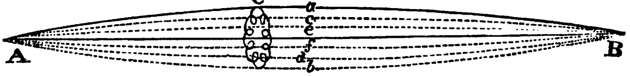
* Introduction to Natural Philosophy. Sec. 15, 43, 44.

59. The vibrations or oscillations thus produced are usually communicated to the surrounding air, which communicates corresponding vibrations to the ear, which recognizes them as sound, provided they be very rapid. The modes of vibration are very different in different bodies. We have already seen how a bell vibrates*; let us now inquire into the modes of vibration of a string stretched tightly between two fixed points A B, Fig. 18. On drawing the string aside with the finger, as in the guitar or harp, or with a bow, as in the violin, or with a hammer, as in the piano, the force employed converts the right line A B into a curved one A *a* B. Now it is obvious that the line A *a* B is longer than A B, and the string, in order to occupy the longer path, must have its fibres or particles separated or strained somewhat further apart. The moment the disturbing force

Fig. 18.



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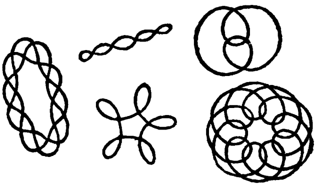
[*] Natural Philosophy. Sec. 15.

ceases to act, the string, by its elasticity, recovers its position A B, but the momentum it has acquired carries it almost as far on the other side of A B as the original displacement, namely, to A *b* B. The friction of the air and the fixed points A B diminish the momentum of the string, so that on the rebound it reaches only to A *c* B, thence to A *a* B, the oscillations still go on, diminishing to A *e* B, to A *f* B, and, finally, to a state of rest.

The motion of any one point in this string is seldom merely backwards and forwards in a straight line, or even in an ellipse, but more frequently it describes such curves as that shown at C, Fig. 18, or those in Fig. 19, indicating actions of extreme complexity, arising from the various unknown molecular forces of the solid.

Fig. 19.



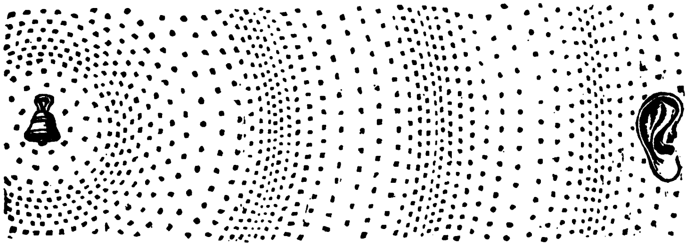
60. Now it must be remarked, that whether these vibrations be large or small they are performed in equal times, because the farther the string is removed from the position of rest the greater is the elastic tension, and consequently the greater the momentum and velocity with which it returns to its original position; and these two elements, the extent of the displacement and the rapidity of the return, are found to increase in exactly the same ratio, a law which applies also to the oscillation of the pendulum.

Every passage of the string over the line of rest A B, Fig. 18, is called a *vibration*, and the mode of comparing two or more velocities of vibration is to choose some small unit of time, such as a second, and to calculate the number of vibrations which occur in such unit.

61. During every vibration of a sounding body the air participates in its motions, and conveys to the ear

a wave of sound. We have endeavoured to represent in Fig. 20 what takes place in the air during the ringing of a bell. Every vibration of the bell sends forth a circular wave which spreads in every direction. Now as these vibrations are *isochronous*, or equal-timed, all the concentric circles are equidistant, like those which proceed from the place where a stone has been dropped into water. Such waves spreading through the air, and therefore breaking upon the ear at *equal* intervals, constitute a *musical note*. In a *noise*, or unmusical sound, the waves follow each other like those of the sea, with no regularity either in their intervals or their intensities. The more regular they may be, the more clear or musical is the sound. The waves of sound are of course not circles but spheres, not spreading in one plane only but upwards, downwards, and on every side.

Fig. 20.



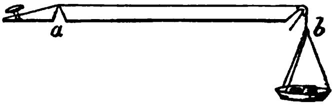
It is further necessary, to constitute a musical note, that the waves succeed each other at least sixteen times in a second, otherwise they will be each heard separately, constituting a *rattle*. But when they are just too rapid to be distinguished separately, they form a very *low* musical note; and the more rapid the higher will be the note. A shrill whistle is due to several thousand vibrations in a second.

62. Now let us suppose the number of vibrations

of a certain string are 100 in a second. On shortening the string we increase the number of vibrations per second in the very same ratio (inversely); so that it will, if shortened exactly one-half, have its vibrations exactly doubled: it will vibrate 200 times in a second, and this will yield a note exactly an *octave* higher than the former one *.

63. But if, instead of varying the length of the string, we vary the *tension* or force with which it is stretched, we get different results, for the rapidity of vibration is found to be increased as the square root of the tension. Let the string be arranged as in Fig. 21, where one end is fixed securely by a peg; the string then passes over a wedge and a pulley, and is stretched by a weight, the effective vibrating length of the string being that situated between the two points of support. Let us suppose the string to vibrate 100 times in a second. Now in order to make the vibrations *twice* as rapid, we must increase the weight *four* times: to make them *three* times more rapid, the weight must be increased the square of three, or *nine* times, and so on. The same arrangement will also prove the fundamental fact, that below a certain rapidity of vibration no sound is produced. If the stretching weight be very small the vibrations will be sufficiently slow for the eye to follow them, and if the number be less than 16 in a second no sound will be heard.

Fig. 21.



64. The reader may be surprised at the number of vibrations made by these strings in a second, and may

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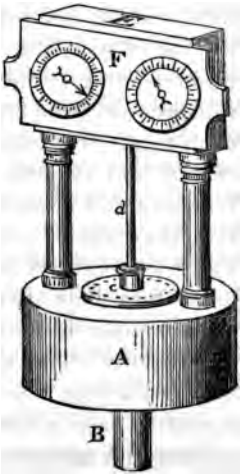
* By doubling the thickness of a cylindrical string we obtain four times the bulk or mass, and we get the number of vibrations doubled in the same space of time. In order, therefore, to study the effect of length only, we must have strings of the same thickness.

wish to know by what means these high numbers are ascertained. We will endeavour to inform him; but first it is necessary to remark, that the same note produced on any musical instrument is due to the same number of vibrations per second. Thus the tenor C, which is produced by a string vibrating 256 times in a second, as in a piano, is also produced in the flute by a column of air vibrating the same number of times per second, and also in the human voice by two chords (called the *chordæ vocales*) contained in the upper part of the windpipe, also vibrating the same number of times per second. And however different the quality of these notes, as given by different instruments may be, they all agree in *pitch*, and this is determined by rapidity of vibration.

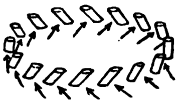
65. There are various methods of determining the number of vibrations per second required for the production of any note. An ingenious little instrument, called the *Syren*, has been invented for this purpose. It is represented in Fig. 22, in which A is a cylindrical chamber of brass. In the instrument used by the writer, this chamber is 3 inches in diameter, and $1\frac{3}{8}$ inch high. A pipe, B, $3\frac{1}{2}$ inches long, screws into an orifice in the lower part of this chamber and fits the tube of a double pair of bellows, or other machine capable of supplying an equable blast of air. The upper surface of the air chamber, which is called the *table*, is pierced with 25 equidistant holes arranged in a circle. A disc *c*, about $1\frac{1}{2}$

Fig. 22.



inch in diameter, containing the same number of holes as in the table, and coinciding with them, is supported by a vertical axis, *d*, having one bearing below the top of the chamber A, and the other in the box E. The disc *c* is so placed as just to turn freely without touching the table, and the holes through it are bored in a sloping direction, as shown in Fig. 23, while those in the fixed table slope the contrary way, so as to deliver the wind in the directions shown by the arrows, and thus turn the disc after the manner of a smoke-jack.

Fig. 23.



The vertical axis *d* is furnished at its upper extremity, where it enters the box E, with a perpetual screw, which gives motion to a wheel furnished with 100 teeth, and its axle bears one of the hands of the dial shown in front of the box. A single cog on this axle also acts on another wheel of 40 teeth, turning the other index, which accordingly moves over one of the 40 divisions of its dial for every complete revolution of the former index, which revolution corresponds to 100 revolutions of the disc *c*. Now it is obvious, that during each turn of this disc, the currents of air through it are cut off and reopened 25 times. The circle of holes, both in the disc and in the fixed table, being equidistant, they are all opened and all closed simultaneously, like the apertures of a revolving ventilator; and the hands and dials afford an exact register of the number of these openings and shuttings up to 25 × 100 × 40 = 100,000. The wheels are fixed to the front plate only of the box E, and this plate can be shifted through a small space sidewise, so as to throw the wheels out of gear in a moment.

When this instrument is placed in connection with a double bellows, the stream of air enters the chamber, where it undergoes a slight condensation: it escapes rapidly through the holes in the table, forming a series of oblique jets which set the disc in motion with a rapidity depending on the strength of these currents, and as the air is strongly propelled when the apertures of the table and of the disc coincide, and is suddenly arrested between each coincidence, it follows that each of these alternations agitates the surrounding atmosphere, so that each revolution of the disc produces 25 waves of sound. These waves originate simultaneously from each of the 25 holes; for if either the fixed or the moving plate had only *one* hole (the other having 25), it is evident that the blast would flow and be arrested the same number of times, and would therefore produce the same *note*, but with less intensity. The use of having 25 holes in each plate is simply to strengthen the note without changing its pitch, on the same principle that the three strings given to each note of a grand piano-forte, without making the pitch of the notes differ from that of a single-stringed harpsichord, improves the power and quality. By regulating the force of the blast, and consequently the speed of rotation of the disc, sounds may be produced from the gravest to the most acute. Let us suppose that by means of this instrument we wish to ascertain the number of vibrations necessary to the production of a note yielded by an organ pipe. For this purpose the pipe is screwed into the upper table of the bellows which supplies air to the syren. The action of the bellows will cause this pipe to sound, and its pitch, as will be explained presently, will not be altered whether the blast be moderate or strong. In the syren, however, the disc will rotate slowly or rapidly in proportion to the strength of the blast, and the resulting note is acute in proportion to the rapidity of rotation. It will be easy to regulate the blast so as to make the syren yield a note strictly unisonant with that of the organ pipe; and we know that notes in unison of the same pitch are due to the same number of waves or vibrations per second. Now as the dial plates of the syren indicate the number of waves generated during the time the wheels are kept in gear, it is obvious that this number, divided by the number of seconds during which they were so kept, will give the number of vibrations per second for the note under consideration. A pendulum beating seconds must therefore be at hand.

A moderate degree of practice in the use of this instrument will enable the observer to determine the absolute number of vibrations per second necessary to the production of any given note without a greater error than one vibration in five seconds. Such observation may be prolonged during several minutes, and thus any small error arising from irregularities in the mechanism will scarcely appear in the result.

The syren may be set in action by the flow of air or gas from a gasometer, or by means of a stream of water. When plunged entirely in water, it will yield the same tones as in air, a circumstance which suggested to the inventor the name of this instrument.

Variations in the number, the form, and the size of the apertures of the rotating disc produce corresponding variations in the *quality* of the resulting notes; the *pitch* or rapidity of vibration may remain the same, but the quality or *timbre* may be very different. This is occasioned by some ill-understood connection between the molecular constitution of bodies and the sounds they emit, whereby we are able to call things by their right names from the sounds they emit. It is a most obscure and difficult subject, and the variations in timbre in the syren do not serve to enlighten it. If the spaces between the apertures in the rotating disc be very small, the tones approach in character to those of the human voice; if the spaces be large, the tones resemble those of a trumpet. A number of experiments with the syren seem to show that the extreme limits of the human voice in males vary from 384 to 1266 vibrations per second, and in females from 1152 to 3240. The highest note in music is about the 14th C* (five octaves above the middle C of the piano-forte), and this is due to 8192 vibrations per second; but much higher tones can still be heard. Savart has produced tones due to 48,000 vibrations per second.

66. Let us now inquire further into the relation between musical pitch and the rapidity of vibration. It has been already stated (62) that, whenever two notes differ by an *octave*, the upper is due to two vibrations for every one of the lower notes; and, as 8192 vibrations per second produce the note called C, it follows that the next C below this contains 4096, the next 2048, the next 1024, then 512, 256, 128, 64, 32, and 16 vibrations per second, the last number being generally considered the lowest note in music, and is also C, being nine octaves below that first mentioned.

67. It would thus appear that in any series of notes taken at equal *intervals*, or in arithmetical progression (according to the musical notation), the vibrations really increase or diminish in *geometrical* progression; for that which the musician calls equal *intervals* or *differences* of pitch, actually indicates equal *ratios* between the times of the vibrations. But, although this is true not only of the intervals called octaves, but also of those called *thirds*, *fourths*, *fifths*, &c. (if

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* So called from its number of vibrations per second, being the 14th power of 2, or $2^{14} = 8192$. All other powers of 2 also give the note C.

perfect), yet it is not true of those called *single tones;* for, if we interpolate six geometrical means between any note and its octave, these will not be the six intermediate notes used in music. The reason for this is as follows:—

We have said (61) that, to constitute a *musical* note, the waves or pulses of air must recur in a *regular* manner. They need not be all equal in intensity or at equal intervals, but their whole cycle of changes (if any) must occupy a very short fraction of a second, and recur in exactly equal periods. Now, when two notes are heard together, they cannot form a compound sound, fulfilling this condition, unless their times of vibration bear a simple numerical ratio to each other, so as to have a short common multiple which forms the cycle of changes above mentioned, and must not be longer than $\frac{1}{16}$th of a second. Accordingly all the intervals called *harmonic* arise from some very simple ratio between the vibrations, as, for instance, the *octave* already mentioned; the *fifth*, when 2 vibrations of one note exactly correspond to 3 of the other; the *third*, when 4 vibrations correspond to 5; the *fourth*, when they are as 3 is to 4, &c. But two vibrations which are incommensurable, or have no common multiple (or a very long one), produce by their combination such a total irregularity, however regular they may each be separately, that the compound loses all musical character, and becomes a mere *noise*.

Hence we see it is the object of the musician to fix on such notes as may afford, among themselves, the greatest number of simple commensurable ratios. This object would be entirely defeated by a geometrical progression (that is, by dividing each octave into *equal* intervals), for no geometrical means that can be inserted between any number and its double will be commensurable with those numbers, or with each other; so that all notes thus chosen must be discordant.

But the required object is best attained by inserting between a note and its octave, or double vibration, six other notes which are respectively due to $1\frac{1}{8}$, $1\frac{1}{4}$, $1\frac{1}{3}$, $1\frac{1}{2}$, $1\frac{2}{3}$, and $1\frac{7}{8}$ more vibrations per second than the lower note, which is called C, or *Do*, while the others represent the remaining notes of the gamut, namely,

D	E	F	G	A	B.
Re	*Mi*	*Fa*	*Sol*	*La*	*Si.*

Hence, supposing that whatever be the number of vibrations per second necessary to produce the note C, we agree to represent it by unity or 1, then the numbers necessary to produce the other seven notes of the octave above will be as follows:—

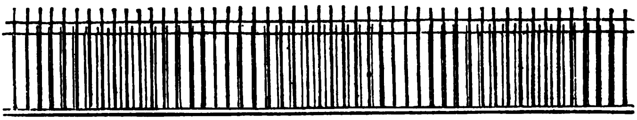
$$D = \tfrac{9}{8},\ E = \tfrac{5}{4},\ F = \tfrac{4}{3},\ G = \tfrac{3}{2},\ A = \tfrac{5}{3},\ B = \tfrac{15}{8},\ C = 2.$$

It will be observed, that the seven intervals or *tones* are by no means equal, for these numbers do not form a geometrical progression. Thus the ratio between C and D is that of 8 : 9, while that between D and E is rather less, namely, as 9 : 10; the next, or that between E and F is only as 15 : 16; the next, or that between F and G, as 8 : 9; that between G and A, as 9 : 10; that between A and B, as 8 : 9; and the last, or that between B and C, is only as 15 : 16. Thus we see that the intervals between E and F, and between B and C hardly exceed the half of each of the other intervals. Hence the reason that these two intervals do not, like the others, admit of subdivision into semitones.

68. A very remarkable proof of the vibratory nature of sound is heard when two notes very nearly, but not quite unisonant, are sounded together. A periodical

interruption of the sound called a *beat*, occurs at intervals which are *longer*, the nearer the two notes approach to perfect identity, and may often be as long as half a second or more. To understand this, we must remember that each pulse or vibration of air consists of *two* contrary motions *to* and *fro*. Now, if one source of sound tend to produce the forward motion exactly when the other source would excite a backward motion, and *vice versâ*, the two, if equal, will annihilate each other, and *two sounds will produce silence*. But with two notes, very slightly differing in pitch, this must occur at certain regular periods, between which the contrary effect takes place, and the two vibrations coincide so as to reinforce each other. The effect is precisely similar to that which is *seen* when two very regular sets of parallel lines, one having rather wider spaces than the other, are superposed. Thus, two iron gratings or railings, Fig. 24, which,

Fig. 24.

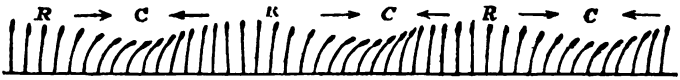


though really of equal intervals, are made to appear slightly different from the effect of perspective, produce the appearance of broad *beats*, or alternations, in one of which the bars coincide and conceal each other, while in the next they fall into each other's intervals. Or to take a closer analogy from the sense of hearing instead of that of sight: if we listen to a train drawn by two locomotives whose driving wheels differ slightly in size, their beats are heard distinctly for a few seconds, they are then lost in confusion for a short time; they are again heard distinctly, and again blended together alternately. Now, suppose any vibrating body to strike the air 100 times in a second, and another 104 times in the same space, the latter will produce a sound about $\frac{1}{3}$rd of a tone sharper than the former; the waves of sound will coincide and reinforce each other 4 times every second, and will oppose, and, if equal, will destroy each other 4 times in the same period, thus producing an audible beat about as rapid as that of a watch.

69. In our introductory treatise on Natural Philosophy, we have shown the method by which the velocity of sound in air has been ascertained. At the temperature of 62° sound travels at the rate of 1125 feet per second. It has been stated (61) that, when a given note is sounded in air, the sound is propagated in *waves* similar in character to those which may be so beautifully studied when the wind is blowing over a field of standing corn. (See Fig. 25.) Now, when it is said that sound travels at the rate of 1125 feet per second, it is not meant that the particles of air move through that distance any more than the ears of corn travel from one end of the field to the other; it is only the *form of the wave* which so travels. It is the same with the particles of air; their individual movement is confined within narrow limits, but the effect of this movement is propagated from particle to particle with the rapidity of 1125 feet per second. As soon as the particles first disturbed have moved to such a distance as their elasticity will permit, they return to their former position, and acquire in so doing a momentum sufficient to carry them a certain distance in the opposite direction, and by this means an oscillating or vibrating movement is established. Each particle is disturbed a little later than the one preceding it, and thus the particles are in different states

of motion, some moving onwards while others are moving backwards, the two sets being separated by particles at rest, or in the act of *turning* from the completion of one movement to commence the next. Now these turning sets of particles are alternately more *condensed* and *rarefied* than in their natural condition. (See Fig. 20.) Those which have just commenced their backward motion are rarefied as the ears of corn at R R R, Fig. 25, and those which are beginning their

Fig. 25.



forward motion are condensed as at C C C.

This has given rise to the term *wave* of sound, a wave being understood to include particles in all the various states of vibration, each wave being exactly similar to all the others for any given note. The *length of a wave* is the distance between any two particles which are in precisely the same stage of vibration. It matters not whether we measure it from the most *forward* to the most forward set of particles, or from the most *backward* to the most backward set; or from one place of greatest *rarefaction* to the next, or from one place of greatest *condensation* to the next; just as it is a matter of indifference, in estimating the length of a wave of water, whether it be taken from one *elevation* to the next, or from one *depression* to the next.

Waves of water do not all travel with the same speed, their speed being proportional to the square root of their length, so that, the slower or less frequent the oscillation, the faster does it travel; those of the ocean, for instance, travel faster than those of the English Channel, and these than the waves of a river.

Waves of air, however, whatever their frequency, all travel with the uniform speed of about 1100 feet in a second. Hence, when we know their frequency, or how many of them arrive at and pass a fixed point in a given time (such as a second), we may at once find their length, which is 1100 feet, divided by their number per second. Thus, the C above the tenor C is produced by 512 vibrations per second; 512 waves fall on the ear in that time, during which each would travel 1100 feet, so that this distance contains 512 waves, each of which must accordingly occupy about 2 feet 1 inch. Consequently, every time this note is sounded on *any* instrument, the air which conveys this note to our ears is thrown into waves, each of which measures about 2 feet. All the innumerable particles of air between us and the instrument form a series of little pendulums, the amplitude of whose oscillations depends on the *loudness* of the sound, and is, in all cases, very minute; but the distance from each particle to the next, which is in precisely the same part of its oscillation as from C to C or R to R, Fig. 25, depends entirely on the *pitch*, and is, in this case, about 2 feet. In the same way we find the waves of the gravest note to be about 64 feet long, and those of very shrill sounds to be less than an inch*.

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* A very curious effect of the rapid motion of the observer on sound has just been brought before the notice of the British Association by Mr. Scott Russell. He found that the sound of a whistle on an engine, stationary on a railway, was heard by a passenger travelling in a train in rapid motion to give a different note, in a different key from that in which it was heard by the person standing beside it. The same remark applies to all sounds. The passenger in rapid motion heard them in a different key, which might be either louder or lower in pitch than the true or stationary sound. Now, as the pitch of a musical sound is determined by the number of vibrations which reach the ear in a second of time, if an observer in a railway train move at the rate of 56 miles an hour *towards* a sounding body, he will meet a greater number of undulations in a

70. When waves of sound meet any fixed surface tolerably smooth, they are reflected according to the law of equal angles of incidence and reflexion. In this way *echoes* are produced. Between two parallel surfaces a loud sound is reflected backwards and forwards, and several echoes are audible. When the parallel surfaces are much nearer together, as the walls of a room, although a larger number of echoes are produced, yet they follow each other too rapidly to be distinguished, and, as they arrive at the ear after *equal* intervals, they produce a *musical note*, however unmusical the original noise may have been. Hence all the phenomena of *reverberation*. The pitch of the note depends solely on the distance of the two walls that produce it, and may be calculated therefrom.

A noise may also produce a musical echo by being reflected from a large number of equidistant surfaces receding from the ear, so that the sound reflected from each surface may arrive successively at equal intervals. Thus a shrill ringing will be heard on stamping near a long row of palisades. A fine instance of the same kind is said to occur on the steps of the great pyramid. If the distance from edge to edge of each step were two feet one inch, the note yielded would be the tenor C, beause each echo having to go and return would be four feet two inches later than the previous one, which

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second of time than if he were at rest, in the proportion which his velocity bears to the velocity of sound. But, if he move *from* the sounding body, he will meet a smaller number in that proportion. In the former case he will hear the sound a semitone higher, and in the latter a semitone lower than the observer at rest. In the case of two trains meeting at this velocity, the one containing the sounding body and the other the observer, the effect is doubled in amount. Before the trains meet the sound is heard two semitones too high, and, after they pass, two semitones too low, being a difference of a major third.

is the length of the waves of that note. But as the steps gradually diminish in size upwards, the echo, if produced and heard at the bottom, must gradually rise in pitch.

These facts explain the principle of those wind-instruments in which there is no vibrating solid. The vibrating body is not the pipe, but the air contained in it. An agitation produced in the air at one end of the pipe is communicated to the other end, and reflected backwards and forwards from end to end, producing isochronous (or equal-timed) impulses, the frequency of which depends entirely on the *length* of the pipe. Hence all organ pipes of the same length yield the same note as to *pitch*, its *quality* only being affected by the form or material of the pipe. It will thus be at once perceived that the lowest C (the waves of which are 64 feet long) requires a pipe of 32 feet to produce it; and that all notes from this, to the shrillest whistle, are easily calculated, by dividing 550 feet by the length of the pipe.

71. Some very remarkable effects of sound are produced in the phenomena of *sympathetic* vibration, numerous instances of which must be familiar to the reader. If a flute be sounded in the same room with a piano, the notes of the flute will cause some of the wires to vibrate. The waves of sound set in motion by the flute produce motion in those very wires which yield the same notes as are being played. If the voice be pitched to the same note as that yielded by a glass goblet, the former will set the latter ringing. And to take a still more remarkable instance, if two pendulum clocks standing against the same wall be both wound up, and one set going while the other is at rest, the small vibrating impulses of the going clock will gradually communicate motion to the pendulum at rest,

and in the course of some hours the latter will be found in full swing.

72. It will be seen from the foregoing survey, that the atmosphere, like a vast and complicated machine, has a variety of movements, the result of omniscient design. Some of the latest and most valuable discoveries respecting the motions of the aerial currents beautifully illustrate a passage in Scripture: "The wind goeth towards the south, and turneth about unto the north; it whirleth about continually, and the wind returneth again according to his circuits."* Amidst all the mutations of science it is cheering to the student to notice, that no sooner is a natural law brought to light and fairly established than we immediately perceive its harmony with sacred truth. Whatever discrepancies may seem at present to exist arise from the imperfection of our knowledge of natural laws, and will, as science advances, gradually be cleared away.

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* Eccles. i. 6.

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